USE OF PARAMETRIC MODELLING AND CLIMATE-BASED METRICS FOR THE EFFICIENT DESIGN OF DAYLIGHT STRATEGIES IN BUILDINGS WITH COMPLEX GEOMETRIES

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Abstract

Daylight devices are important components of any climate responsive regular façade systems. But, the evolution of parametric CAD systems and digital fabrication has had an impact in architectural form and regular forms are shifting to complex geometries. Architectural and engineering integration of daylight devices in envelopes with complex geometries is a challenge in terms of their design and performance evaluation. The purpose of this research is to assess daylight performance of buildings with climatic responsive envelopes with complex geometry that integrates shading devices in the façade. To this end two case studies are chosen due to their complex geometries and integrated daylight devices. The effect of different parameters of the daylight devices is analysed through Climate base daylight metrics (CBDM). The case studies are based on the Esplanade buildings in Singapore and Kunsthaus Graze in Austria. Climate base daylight metrics such as Daylight Availability and Useful Daylight Illuminance are used. DIVA (daylight simulation), and Grasshopper (parametric analysis) plug-ins for Rhinoceros have been employed to examine the dynamic range of performance possibilities. Parameters such as dimension, inclination of the device, projected shadows and shape have been change in order to maximize Daylight Availability and Useful Daylight Illuminance while minimizing glare probability. The results show that while Esplanade building orientation did not have a great impact in the results, aperture of the shading devices with a projection of 1.75 m and 2.00 m performed best, achieving target lighting levels without issues of glare. Also nozzle orientation from the east and south did have a great impact in the results, aperture of the nozzle devices with a projection of 0.75 m performed best achieving target lighting levels in Kunsthaus Graze.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

CBDM	Climate-Based Daylight Metric
GH Plug-in	Grasshopper Plug-in
DA_V	Daylight Availability
UDI	Useful daylight Illuminance
DGP	Daylight Glare Probability
DA	Daylight Autonomy
DF	Daylight Factor
NURBS	Non Uniform Rational Basis Spline

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: QUT Verified Signature

Date: March 2015

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Chapter 1: Introduction

1.1 BACKGROUND

Daylighting is a very important factor in the design of a building and could impact on the shape of a building (Bell 1973). Preferences of daylight quality and quantity in building interiors, affects building shape and orientation, and the façade through the design of the openings such as orientation, placement, size, shading and complexity. The façade plays a crucial role as a responsive and active controller of the interchanges occurring between the external conditions and internal environment in a building (Shameri, Alghoul et al. 2011). Also, it is one of the most important methods to save energy inside the building (Wang, Wong Nyuk et al. 2007). The façade of buildings are designed to respond to different issues such as function, environment, occupant comfort, energy consumption, sustainability, economy, technology and aesthetics (Poirazis 2008).

Daylight systems are optical devices placed or integrated into openings on any conventional façade system and their function is twofold. Firstly to capture daylight and redirect it to the building interior, and secondly to protect the building interior from solar radiation (Garcia-Hansen 2006). Daylight devices can be operated both automatically and manually to control daylight performance (Headquarters, Tower et al. 2007) and these examined in this study either reject light as a shading devices or redirect light. Redirecting or guiding systems were normally grouped as vertical elements (e.g. laser cut panels, prismatic panels), horizontal elements (light shelves) and parabolic collectors (Garcia-Hansen 2006). Design which combine daylight devices and façade systems pose architectural problems and can have a negative aesthetic impact and lack integration with other components.

Parametric modelling is a way to combine façade system with other components. The evolution of parametric modelling and digital fabrication has impacted architectural form and regular forms are shifting to complex geometries (Scheurer 2010). Parametric modelling not only allows the generation of new forms in architecture but also enables designers to automatically generate a large range of alternative design solutions supporting geometric design explorations (Turrin, von Buelow et al. 2011).

Previous studies in complex geometries and daylight responsive envelopes (Turrin, von Buelow et al. 2011; Henriques, Duarte et al. 2012; Varendorff and Garcia-Hansen 2012) assessed daylighting performance based on static simulations (on selected days and times) using daylighting levels based on standards or Green building rating tools such as LEED (North America), BREEAM (UK) and Green star (Australia). The shortcomings of these static daylighting simulations have been explained elsewhere (Nabil and Mardaljevic 2006; Reinhart and Wienold 2011). So a better approach to the analysis of daylighting in building design may be the use of Climate-Based Daylight Modelling (CBDM). CBDM is the prediction of luminous quantities using realistic sun and sky conditions derived from standardized meteorological data (i.e. hourly values for a full year) (Mardaljevic 2011).

1.2 PURPOSES

1.2.1 Aims of research

This research models parametrically buildings with complex geometries and integrated daylighting devices to evaluate their daylight performance, with the aim of finding optimum solutions that could maximize natural light while reducing issues with glare in the buildings. The modelling and optimization of these strategies produces a complex interaction between the facade system and daylight devices in the building. Integrated parametric facades and daylight devices establish a tight connection with building energy, control systems and design surface (aesthetics) buildings. The steps followed to find the optimum design of complex geometries with daylighting devices are to:

- Model a façade and daylight system, based on parametric design using Grasshopper plugin in Rhino
- Develop a coupled model of façade system and daylight devices
- Investigate façade system on daylighting performance
- Compare the effect of daylight device position on glare potential in interior space

- Specify the optimum daylight device position regarding the climate-based method

1.2.2 Research questions

Specific research questions of the research are:

1. How do geometrical characteristics of daylight devices affect daylighting performance in buildings with complex geometries?
2. How can the integration façade and daylight system be improved in terms of sustainable design?
3. How effective is the climate-based method for analysing natural light on buildings?
4. What is the effect of daylight analysis on building design from the designer and engineer points of view?

1.2.3 Objectives

The objective of this research is to understand effect daylight device configuration has on the daylight performance to obtain visual comfort in the building. Reducing glare probability in interior space regarding to climate based daylight metric analysis is also important. Therefore the detailed objectives are as follows:

- Combine the capabilities of parametric modelling with the use of CBDM to assessment the effect of different parameters of daylighting devices (such as length, inclination, device geometry) on the daylight performance of a building with a climatic responsive envelop with complex geometry.
- Integrate daylight devices and envelope facades to improve the performance of any new surface design by analysing the conserving daylighting performance.
- Evaluate the design explorations using CBDM such as Daylight Availability, Useful Daylight Illuminance in addition to Glare Probability.
- Improve the design of daylight devices in buildings, with-in complex façade systems.

1.3 SIGNIFICANCE

Daylight is an abundant natural resource that can provide useful light to interiors and is associated with other benefits such as view and lowered use of electric light. The quality of daylight is much better than electric light though daylight abundance can also be a negative issue working the control of daylight to an interior a critical element in a successful system (Olbina and Beliveau 2009). Excess daylight can cause visual discomfort as glare, and increased cooling loads for a building. It is important to design a facade system to control daylight appropriately, maximize the benefits of avoid the potential negative outcomes (Vine, Lee et al. 1998). Traditional design principles guide the design of daylighting devices (e.g. vertical and horizontal orientation of fins, louvers and awnings; vertical and horizontal guiding systems) applied to orthogonal planar façades (Varendorff and Garcia-Hansen 2012), but with doubly curved envelopes characterizing many contemporary designs, these rules of thumb are currently not always applicable. Daylighting devices are currently not well incorporated within parametric façade system design processes, making the architectural and engineering integration of daylight devices in envelopes, with complex geometries a challenge, not only in terms of their design but also in terms of their performance evaluation. Findings from this research will assist in providing better methods of designing the envelope facade system, to ultimately reduce CO_2, electricity and promote healthy building.

1.4 THESIS OUTLINE

Chapter 1 presents the background problems and concepts related with the parametric modelling and optimization daylight performance of the building. Included in Chapter1 are also the purposes objective and significance the study of the green building design. Chapter 2 examines the literature on the façade system and daylight devices to control daylight in the building. Chapter 2 also contained the concept of parametric modelling to combine and redesign devices to find the optimum position on the complex geometry design the façade systems. Chapter 3 describes the methodology such as model development, project study design, experimentation and evaluation to optimise the modelling of façade system devices for good daylighting design in the buildings. Description of the simulation softwares (Plug in for Rhinoceros: Diva-daylight and grasshopper-parametric analysis) employed in the parametric modelling and building analysis are presented in Chapter

3 also presents the parametric construction of the two case studies, the Esplanade in Singapore and Kunsthaus buildings in Austria (examples of complex geometries combined with daylighting devices), which their design were recreated to experiment with different parameters of the daylighting devices. Chapter 4 describes the evaluation of the case studies, and presents utilize different parameters to achieve adequate daylight performance in the buildings. This Chapter also shows the CBDM results from the case studies and examines the results. Chapter 5 provides the conclusion and recommendation for further research.

Chapter 2: Literature review

2.1 INTRODUCTION

This chapter provides an overview of the current literature on issues of integration of daylight devices with a façade system, and the effect of parametric design in complex buildings' form, and the provision of climatic responsive envelops with complex geometries. The first parts of this chapter is about building envelope system and include information about double skin façade, curtain wall, the effect of using a façade system to save energy and sustainable design. The second part contains an overview of using daylight strategy in the building design process to improve natural light in the area. The third part examines daylight devices to control daylight inside the interior spaces. Followed by daylight analysis methods to explain the climate-based method for analysing daylight performance in buildings. The last part of literature then present use of digital technologies such as parametric modelling and dynamic process in the architecture and engineering to generate and assess solutions.

2.2 BUILDING ENVELOPE SYSTEM

The façade plays an crucial role as a responsive and active controller of the interchanges occurring between the external and internal environment, and is one of the most important methods to save energy inside a building (Wang, Wong Nyuk et al. 2007). Building facades are designed for different purposes such as function, environment, occupant comfort, energy consumption, sustainability, economy, technology and aesthetics (Poirazis 2008). Façades account for between 15% and 40% of the total building budget, and can be an important contributor of building cost (Wigginton and Harris 2002). This section present more information about building envelope systems including double skin façade, using materials and shading system on the facade.

Double skin façade (DSF)

A double skin façade is the best option to manage interactions between the outdoors and internal spaces (Shameri, Alghoul et al. 2011). The skins in DSF can be airtight or naturally/mechanically ventilated (Baldinelli 2009). The outer skin is usually a hardened single glazing and can be fully glazed. An air-tightened double skin facade can increase thermal insulation for the building and reduce heat loss in cold seasons (Huang 2010). On the other hand, a moving cavity air inside a ventilated double skin facade can absorb heat energy from sun-lit glazing reduce heat gain as well as the cooling demand of a building (Chan, Chow et al. 2009). Double skin facades are usually characterized with both aesthetic design and energy saving. The aesthetic designs for DSF glass are leads to increased transparency. Also, energy saving in DSF is significant for engineers to an improved indoor environment, an improved the acoustic in building located in noise polluted areas and the reduction of energy use (Shameri, Alghoul et al. 2011). Although the concept of DSF is not new, there is a growing tendency for architects and engineers to use it in various design projects (*Figure 2.1*).

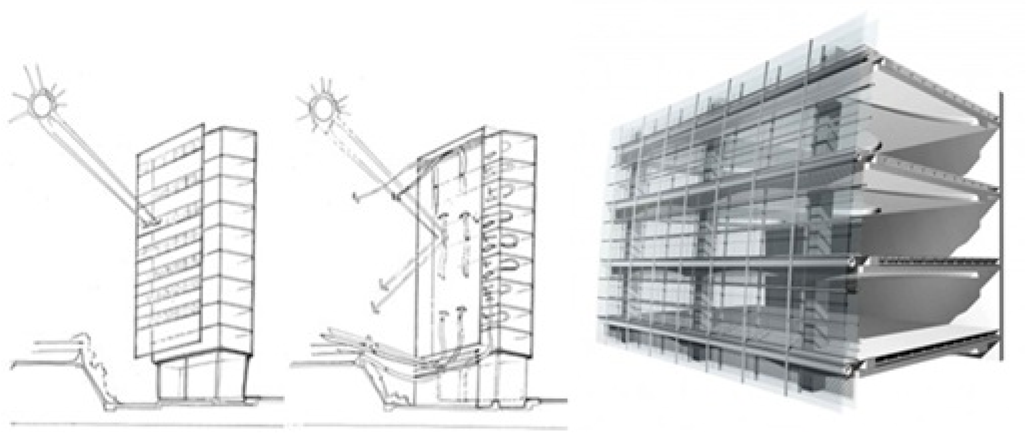

Figure 2.1. Double skin facade system (pricemyers 2004).

Thus the double skin facade system could emphases the following areas (Said 2006):

- aesthetic design, the slick result of fully glazed facades are a tendency followed by architect and developers
- Improvement of environmental profile of building
- Thermal comfort
- Acoustic comfort
- Ventilation
- Energy Use

Material and Glass selection for DSF

Designers should take care when choosing materials to be used with glass and DSF construction to control the light reflection of pane type and daylight device. Double or triple panes are used to control thermal insulating in the exterior skin and single pane is used in internal skin (Poirazis 2008).

Shading devices

Shading devices can be placed on the façade systems and operated automatically and manually to control effect of daylight performance on comfortable area (Headquarters, Tower et al. 2007). The shading devices must be placed close enough to the exterior façade to control natural light in an interior space. However, aesthetics design and environment will produce a different combination of devices on the façade system. Then need to be considered earlier in the design process. Shading devices is discussed in more detail the daylight devices section.

2.3 DAYLIGHT STRATEGY

Incorporating daylight has been a main factor in the design of buildings throughout the history and can be considered foundation to the development of a design and one of the most influential decisions in shaping building (Bell 1973). Daylight has two components: sunlight and skylight. The source of the sunlight and skylight are sun and sky, respectively and many daylight systems are designed to transfer natural light to the interior space. However the challenge in each daylight strategy is to optimize system delivery, daylight performance and minimize the size of the glare area (Boubekri 2008). Daylight strategies are divided into two groups: sidelight system, when daylight is access through a side opening in a wall, and top lighting, when light is brought from the top/ceiling opening.

2.3.1 Side lighting Systems

Most side lighting systems are designed to overcome the problems of high light levels near windows and dark light levels areas away from openings. There are many ways to introduce the natural light into a building adding devices to the window glazing such as side window, light shelves and prisms.

Side window

One of the most common daylighting systems is side windows. Windows can provide different light intensities of daylight based on different window sizes, glass material, frame design, orientation, and time of day; season, and climate. Vertical windows are the most common type of daylighting system (Huang 2010). The useful depth of a daylighting area range is typically limited to 1.5 times the window head height (Heschong, McHugh et al. 2005). With a reflective light shelf, this area may be extended up to 2.5 times (*Figure 2.2*). Corridor beyond this zone and separated with a partially glazed wall may be adequately lit with the spill light from the room. Adequate distance from a standard window and ceiling heights is 4.6 m (O'Connor Jennifer 1997). Side lighting is a way to introduce daylight into a space, however the illuminance reduces with distance from the opening (*Figure 2.3*). The part of the room closer to the window is the most lit, but further from the window natural light is quite poor.

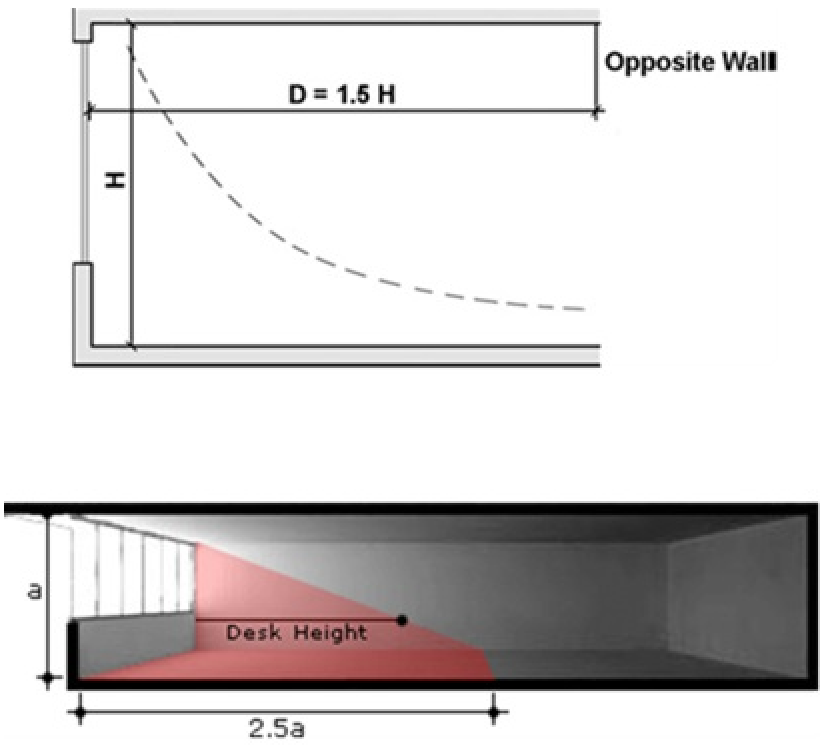

Figure 2.2. Section showing effective depth of daylight penetration (naturalfrequency 1994-2011; Boubekri 2008).

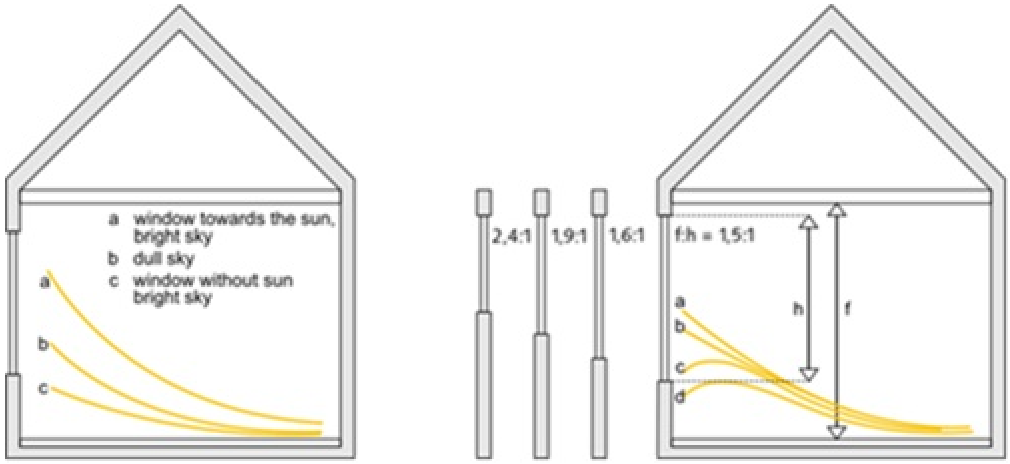

Figure 2.3. Iso-contour curves of daylight penetration (Frankel and Lyles 2013).

Clerestory System

A clerestory is also a side window but placed high in the wall. It usually doesn't effect views in direction of the exterior, but permits a deeper penetration of daylight into the room while a standard side window giving little glare to the occupants of the room. Combining the side-systems to include a side window and clerestory delivers an additional distribution of sunlight penetration (*Figure 2.4*) (Boubekri 2008). The problem with this strategy is that the space needs access to the roof.

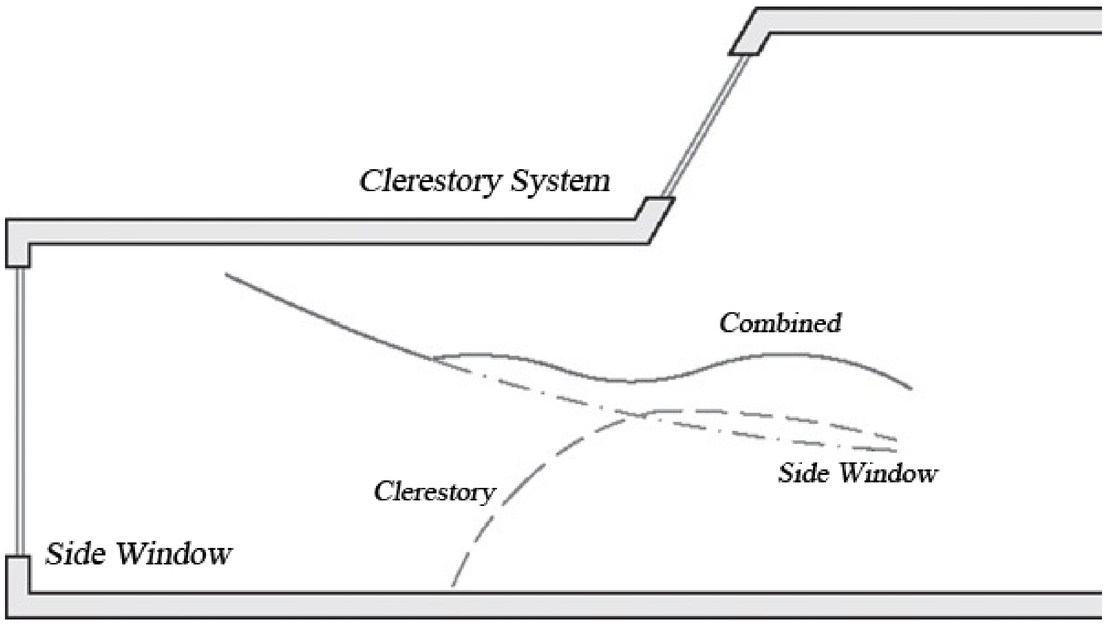

Figure 2.4. Daylight penetration from the combined of side window and an oblique clerestory (Boubekri 2008).

2.3.2 Top Lighting Systems

Skylight System

A skylight system is one simple strategy to capture natural light, give excellent daylight levels, is difficult to control the direction of solar radiation from the sun when it is directly overhead (*Figure 2.5*). This daylighting method can be used only for the top floor of a multi-store building or for single-store buildings (Boubekri 2008). Given their location in the roof, skylights tend to gain and lose heat by convection and conduction more than other types of windows (O'Connor Jennifer 1997).

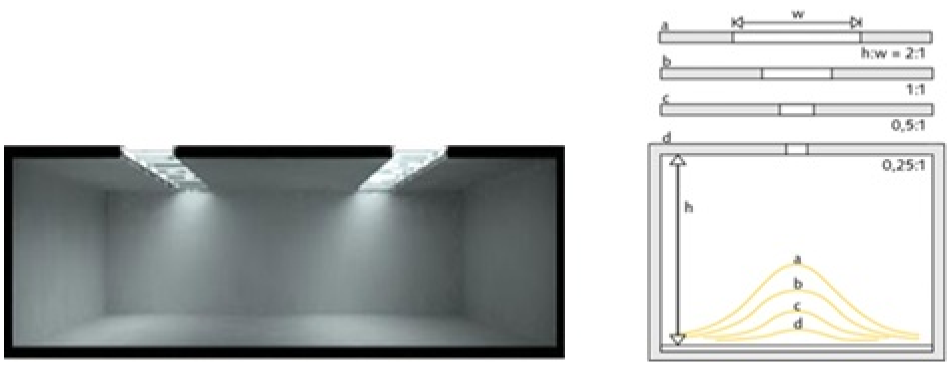

*Figure 2.5.*The effect of skylights on daylight distribution (naturalfrequency 1994-2011; Architecture 2011).

2.4 DAYLIGHT DEVICES

A review of the daylight system for building has novel and innovative daylighting technologies to improve natural illumination of the buildings. That is daylight strategies can be combined with daylighting systems (Garcia-Hansen 2006). This section examines the main types of daylight device systems in buildings such as light guiding system and light transport system.

2.4.1 Light Guiding Systems

The main purpose of light guiding systems is to use direct or indirect light reflected into the building. Usually in tropical and subtropical climates, sunlight intensity is high, so a light guide panel and reflective material on the ceiling enables light to enter the building. This method is energy saving at it decreases the use of electrical lighting (Huang 2010).

2.4.2 Light Shelf System

A light shelf is a horizontal or nearly horizontal baffle designed to capture sunlight particularly into the interior space and shield building from direct glare (Huang 2010). A light shelf divides the window into two parts. The lower part helps to provide the exterior view and an upper window helps redirect the daylight towards the back of the room away from the window plane(*Figure 2.6*) (Boubekri 2008). Such a system should be located high enough to avoid reflected glare, and can be used both in exterior and interior spaces. Interior light shelves are more effective to sunlight capture in to the back of the space (*Figure 2.7*).

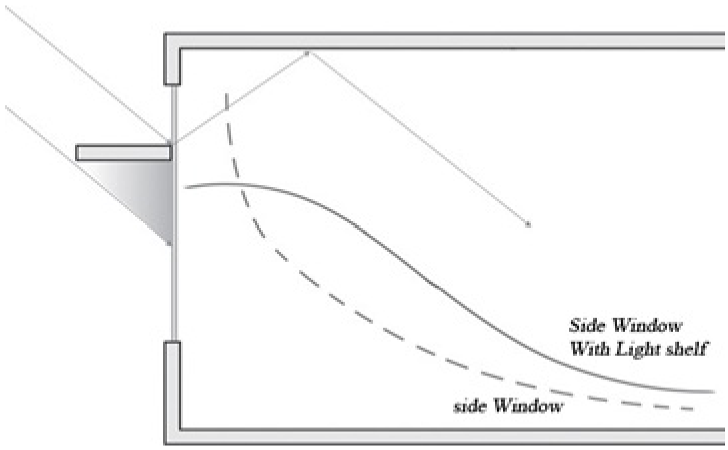

*Figure 2.6.*Sunlight capture with exterior light shelf system (Boubekri 2008; Huang 2010).

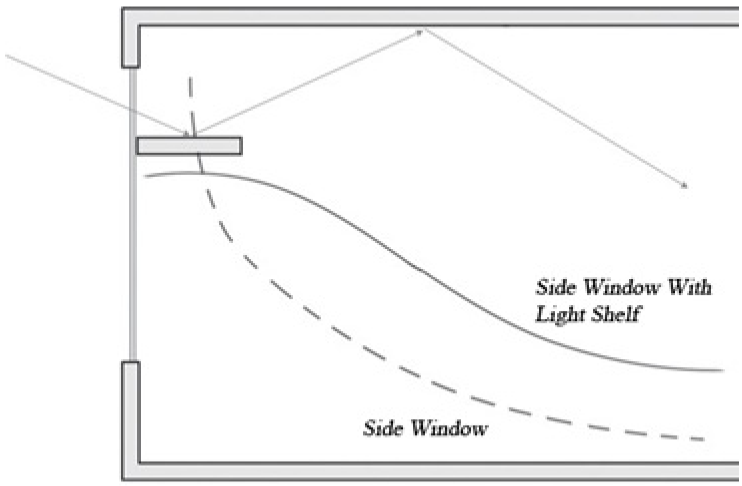

*Figure 2.7.*Sunlight capture with interior light shelf system (Boubekri 2008; Huang 2010).

Using a dynamic system is another way to optimize sunlight penetration, according to the time of day or season. *Figure 2.8* show a reflective film moving between two positions in light shelf device to optimize sunlight reflection. This device can be operated automatically to achieve higher efficiency (Littlefair, Aizlewood et al. 1994; Boubekri 2008).

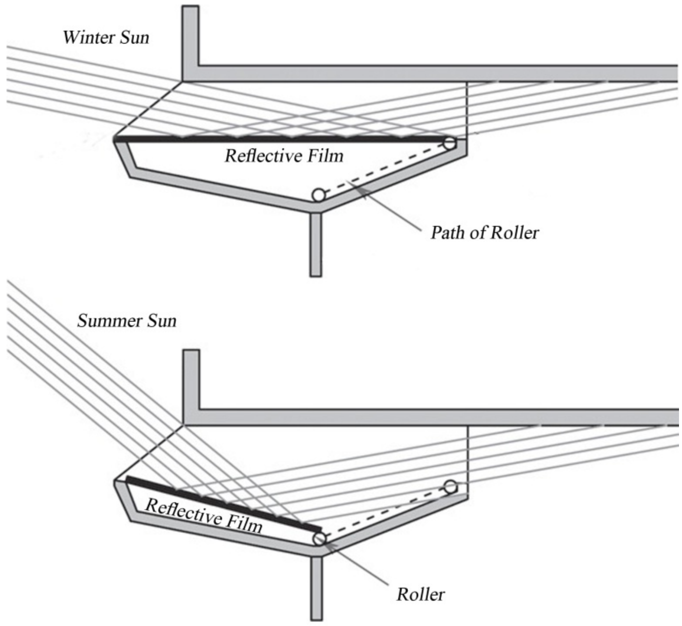

*Figure 2.8.*The variable area light shelf system (Littlefair, Aizlewood et al. 1994; Boubekri 2008).

2.4.3 Louvers and blinds

These systems are a combination of louvers, blinds, sills and scoops (Garcia-Hansen, M.Bell et al. 2006). Littlefair (1990) stated that reflective louvers break direct sunlight from falling on occupants and redirects it to the back of the room through the ceiling. Louvers have been used for many years to provide shade by managing sunlight. The difference with the sunlight is redirected into the room and forms a large diffuse light source on the ceiling (*Figure 2.9*). The aim is to improve light penetration deep within the space Louvers are generally used on the exterior of a facade creating a problem for cleaning and maintenance. This system also obstructs the direct view of the outside (Boubekri 2008).

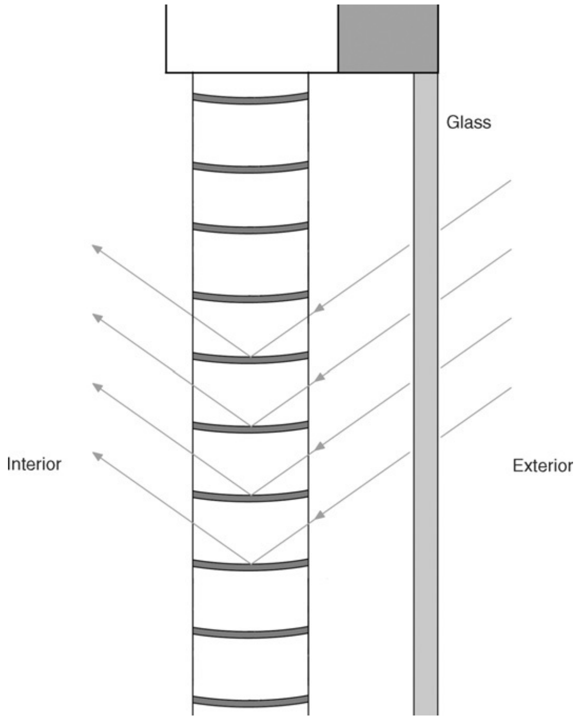

Figure 2.9. Light-redirecting louver system (Boubekri 2008).

2.4.4 Prismatic System

The prismatic panel system works on the principle of refraction to redirect incident sunlight. The panels are serrated on one side forming prisms or have saw tooth linear grooves across the face of the panel (Linhart, Wittkopf et al. 2010). The angles of two sides of the prism are engineered to block certain angles of sunlight and refract and transmit others. For some designs, one or both surfaces of the prism are coated with a high-reflectance aluminium film. The panels should be applied to the exterior of the building and should be adjusted seasonally to compensate for the variation in solar altitude (Lee, Selkowitz et al. 2002).

2.4.5 Laser cut panels

Laser-cut panels developed in Australia use simple linear horizontal cuts in an acrylic panel to refract light at the juncture of the linear grooves. The angle of refraction is a basic material property, so efficiency is dependent on the frequency and spacing of the grooves and thickness of the panel. For practical purposes, there are limits on panel size and spacing within the Insulating Glass Unit (IGU) due to the high coefficient expansion of acrylic (*Figure 2.10*). The view is slightly distorted/impaired and glare is not controlled with this system though channel panels are an improvement from LCP(Lee, Selkowitz et al. 2002).

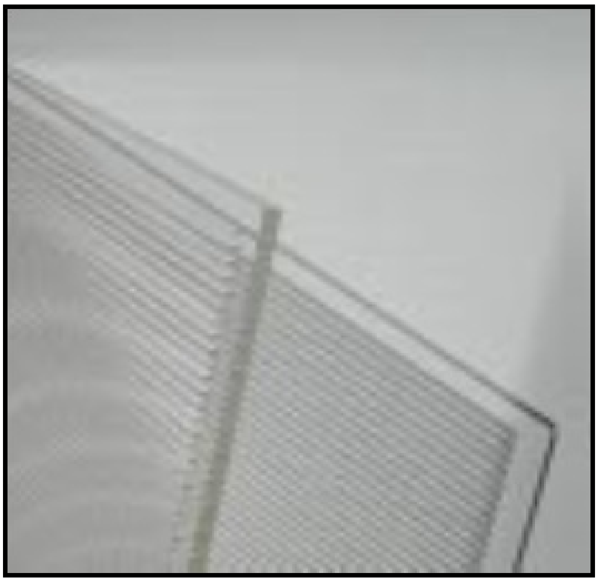

Figure 2.10. Laser cut panel, (Lee, Selkowitz et al. 2002).

2.4.6 Sun Directing Glass

Sun directing glass is long, slightly curved sections of glass stacked and placed between panes of glass. The refractive index of glass is again combined with geometry to redirect sunlight to the ceiling plane (Lee, Selkowitz et al. 2002).

2.4.7 Holographic Optical Elements

Holographic optical elements use the principle of diffraction to redirect sunlight. An interference pattern of any specification can be stamped on a transparent film or glass substrate, and then laminated between two panes of glass. Diffractive optical efficiency tends to be poor, but may improve as technology is developed (Lee, Selkowitz et al. 2002).

2.4.8 Light transport systems

Light transport systems can introduce daylight into deep building interiors, potentially displacing the requirement for electrical lighting (*Figure 2.11*). Garcia-Hansen (2006) describes the light transport or remote source systems as capable of channelling sunlight to areas in buildings that receive insufficient natural illuminance and usually remote from the building envelop. This system has two main components: one for capturing sunlight and another for distributing it within the building. Sunlight is captured by collection structures. Mounted on each floor above the windows along the wall of the building that has the greatest sunlight exposure (West 2001).

Figure 2.11. Light transport system, BCIT NE-25 (Rendering by Busby Perkins + BCIT[1]).

2.5 DAYLIGHT SIMULATION

Several studies have been conducted on architectural lighting design to maximise daylight performance in the building (Oh, Chun et al. 2013). The role of computerized building design tools provides such information efficiently. Reinhart and Fitz (2006) conducted a survey on the current use of daylight simulations in building design and identified that "*daylighting software such as Radiance should be used by specialist*". This survey divided professional participants to the five groups of Architecture, interior designer and lighting designer were grouped into the design group (Reinhart and Fitz 2006). *Table 2.1* and confirmed that 69% of professional designers engineers used software to analyse natural light in the building.

*Table 2.1.*Professional participant group percentage used the daylight simulation on building design (Reinhart and Fitz 2006).

Professional Group	Participant	Percentage %
Designer	58	31%
Engineer	71	38%
Researcher	43	23%
Other	13	8%

Professional groups use different methods such as Daylight factor, Climate-based and Visualization for daylight simulation in the buildings. The next section

[1] http://www.bcit.ca/sustainability/operations/buildings/bbysolarcanopy.shtml

introduces daylight analyses in the buildings and present newest methods for natural light analysis.

2.5.1 Daylight Factor (DF)

Daylight Factor is usually one of the first daylight performance measurements for daylight simulation and newcomer calculations (Ibarra and Reinhart 2009). A DF is the ratio between illuminance due to daylight at a special point on an indoor illuminance at reference point (Ei) and external horizontal illuminanace from unobstructed sky (Eo) in a building. The DF is defined as:

*DF= (Ei/Eo)*100%*

Daylight factor output is helpful for a quick evaluation of relative daylight penetration under overcast sky situations (Frankel and Lyles 2013). Ibarra and Reinhart (2009)worked with 87 students during the analyse one room in the Macdonald-Harrington Building in Montreal, Canada with the DF method to clarify "*how close do simulation beginners really get?*". During this study they analysed DF by using Radiance and Ecotect software and combined the results of these two softwares to compare the quality of DF simulation with climate-based (*Figure 2.12*). This study suggests that DF method cannot be extended to account for the dynamic properties of daylighting (Ibarra and Reinhart 2009).

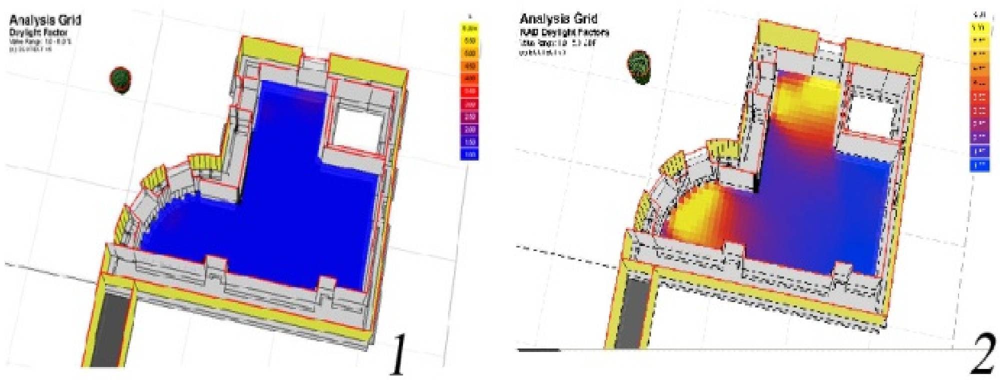

Figure 2.12. (1) Ecotect Daylight Factor Simulation, (2) Radiance Daylight Factor Simulation (Ibarra and Reinhart 2009).

2.5.2 Climate-based

Reinhart and Wienold (2011) proposed computer- based daylight performance analysis and asked "why the design community at large scale is not working with advanced design analysis schemes." These advances moved away from static toward dynamic and climate-based daylight simulation (Reinhart and Fitz 2006). However, five mean barriers of these method has been shows (Reinhart and Wienold 2011):

- No single simulation environment
- Simulation time
- Complicated simulation process
- Out-dated rating schemes
- No clear understanding of simulation outcomes

The first two barriers of no single simulation environment and simulation time are more important, because different technical advances have been realized in different simulation environments and require long computation times (Reinhart and Wienold 2011). For instance, simulation outcome from daylight factor calculated Lux[2] just one time in day. This result is not sufficient for a detailed analysis of natural light in buildings. The climate-based analysed annual amount of daylight performance in space used climate information to simulate (Reinhart and Weissman 2012). These climate-based has performance categories to simulate daylight in an interior space, such as Daylight Autonomy (DA), Continue Daylight Autonomy (CDA), Useful Daylight Illuminance (UDI100-2000lux) and Daylight Availability (DAV). This section explains each part of the climate-based simulation:

Daylight Autonomy (DA)

Daylight Autonomy was the first of a series of annual daylight metrics, now commonly referred to as dynamic daylight metrics. This method represented a percentage of annual daytime regarding to minimum illuminance level at the work plane , and considering the geographical specific weather data to show the specified illumination level (2012). Suisse association proposed the DA and was later improved by Reinhart 2004.

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[2] Lux is the unit of illuminance and luminous emittance

Continue Daylight Autonomy (CDA)

Continue Daylight Autonomy (CDA) was proposed by Zach Rogers (2012) as a basic modification of daylight autonomy and the fractional level of minimum daylight illuminance calculated (Reinhart and Herkel 2000). For example regarding this method when a point receives 300 lux of daylight illuminance and the required illuminance is 500 lux, for this point given daylight is 300/500 or 0.6 for that time step (Wienold 2007).

Useful Daylight Illuminance ($UDI_{100\text{-}2000lux}$)

Useful Daylight Illuminance (UDI) is an conceived adjustment of Daylight Autonomy (Frankel and Lyles 2013). UDI is determined from 100lux to 2000lux on an hourly time value base when daylight level is useful for the occupant. UDI is calculated daylight level in three illumination ranges: 0-100lux, 100-2000lux and over 2000lux. When the useful daylight levels are achieved, daylight level is neither too dark (<100lux) and nor too bright (>2000lux) (Olbina and Beliveau 2009).

Daylight Availability (DA_V)

These metrics are calculated from annual illuminanace profiles on an hourly and sub hourly time series, according to a local weather data (Reinhart and Wienold 2011). As a result, these metrics combine daylight autonomy (DA) and useful daylight illuminance (UDI) information (Reinhart and Wienold 2011). Reinhart and Wienold (2011) considered the side light space case study to purpose a new method to analyse DA_V results (*Figure 2.13*). Which they defined as "*calculate the percentage of the occupied times of the year when a minimum illuminance is met by daylight alone*" (Reinhart and Walkenhorst 2001; Reinhart and Wienold 2011).

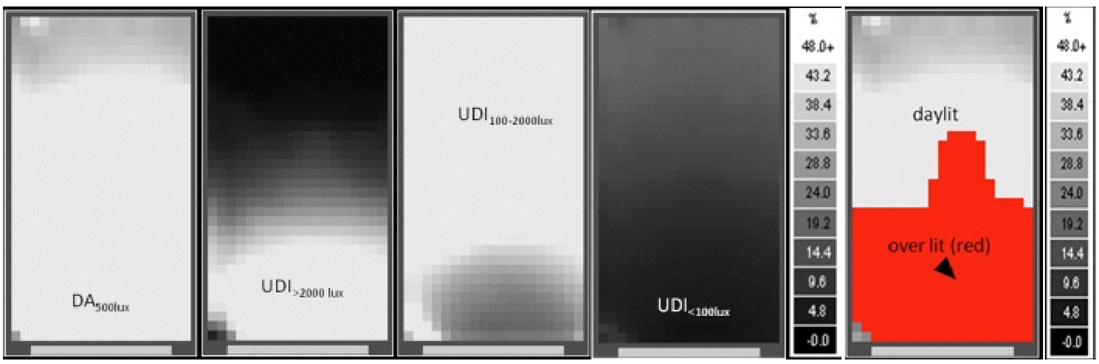

Figure 2.13. Plan view of the Daylight Autonomy, Useful Daylight Illuminance and Daylight Availability in the side light (Reinhart and Wienold 2011).

2.6 PARAMETRIC MODELING

This section present the benefits derived by use of digital technologies such as parametric modelling and dynamic process in the architecture and engineering to generate and assess solutions (Henriques, Duarte et al. 2012). Parametric modelling not only allows the generation of new forms in architecture but also enable designers to automatically generate a large range of alternative design solutions supporting geometric design explorations (Turrin, von Buelow et al. 2011). Parametric modelling has always been basic knowledge in the architectural design process, especially as a design language in the form of drawings based on the rules of descriptive geometry (Eigensatz, Kilian et al. 2010). Also, dynamic process is used to adapt the shape of the modelling to changing parameters regarding to function, location and environment conditions (*Figure 2.14*).

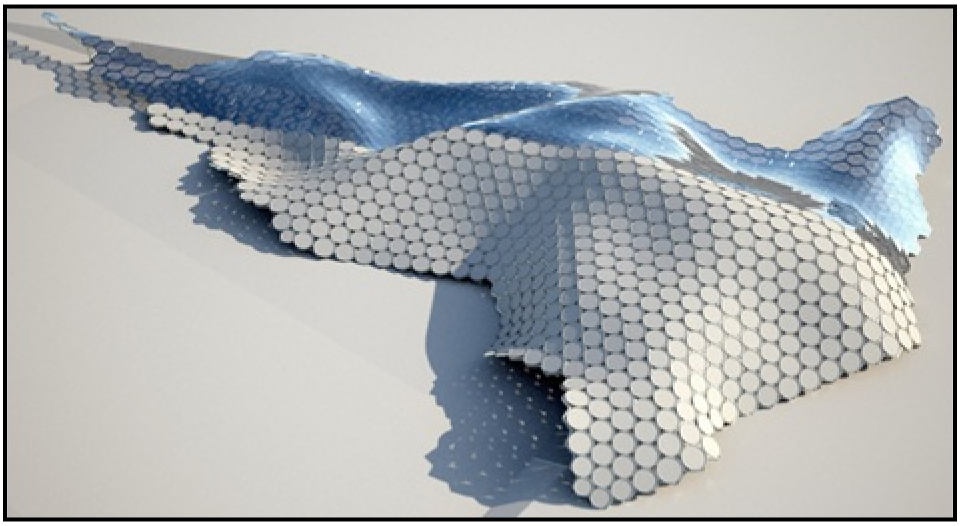

Figure 2.14. Selfridges Department Store, Bullring, Birmingham. UK (Singh and Schaefer 2010).

Dynamic customization is one part of the environment modelling process when the design variations are built and replacing singularity with multiplicity in the design process (Barrios Hernandez 2006). Cardenas (2007) said the geometry of architectural designs is rapidly becoming more complex and challenging. The parametric modelling responds to designers for flexible variations without removing or redrawing with computer abilities (Bollinger, Grohmann et al. 2008; Maria van Embden, Michela et al. 2011).

All parametric design can be categorized into two kinds: the parametric variation (PV) and parametric combination (PC) (Barrios Hernandez 2006). A PV model is a parametric model based on the modification of parameters to construct shapes, and a PC model is composed of a series of geometrical shapes (Nembrini, Labelle et al. 2011). Therefore, Henriques (2012) discuss the benefits derived by combining parametric modelling, dynamic process and static customisation to control parameters on the façade system. The static customisation is obtained during the design process by selecting the parameter of the modelling such as size and arrangement form (Henriques 2012). This research used parametric modelling such as static customisation to develop a responsive system to control skylight in real-time. Also, dynamic process in this study controlled aperture values, weather file, and time to determine the skylight panels on the surface modelling (*Figure 2.15*).

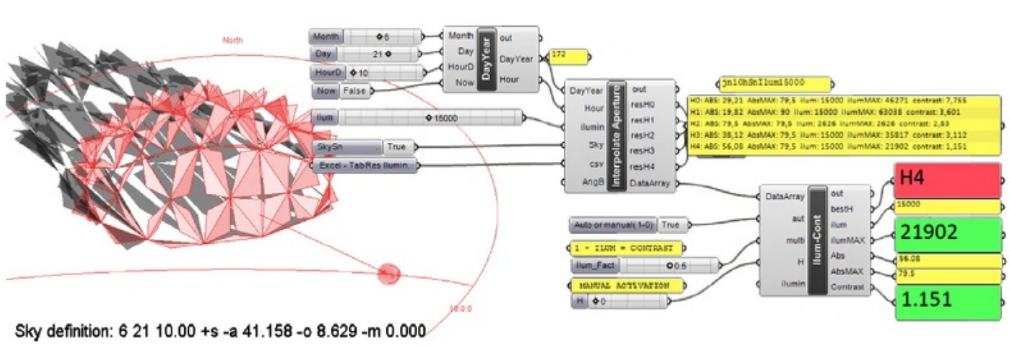

Figure 2.15. Dynamic process and static customisation using parametric software (Henriques, Duarte et al. 2012)

Turrin, von Buelow et al. (2011) discuss the benefits derived by using parametric modelling to achieve a performance oriented process on large surface. Also, this research described the integration of parametric modelling with other computational techniques had been coupled to link a creation complex cladding system in the building. The overall shape of the surface was explored in two ways. The first one used an initial NURBS surface, and the second one used a mathematic function to describe the position of the points (Turrin, von Buelow et al. 2011). The parametric control of overall Shape in this case leads to increasing solar gain, avoiding heat losses in winter time and reducing solar gain in summer time (*Figure 2.16*).

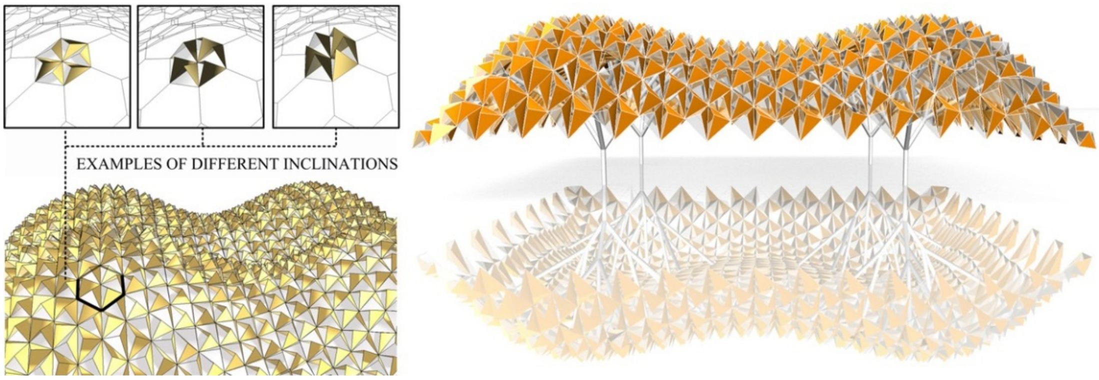

Figure 2.16. Cladding system, showing parametric inclinations of the panel (Turrin, von Buelow et al. 2011).

2.7 IMPLICATIONS

This literature review section discussed the effect of the façade system on building design was. The role of daylight devices to control natural light on interior spaces to establish a comfortable environment, sustainable design and save energy has been described. Therefore, the integration of a façade system with daylight devices is important to achieve a sustainable design. On the other hand, the parametric design method integrates the parametric façade geometry and moveable components on the facade. This method has been used by engineers and designers previously. However, recent developments in software packages means more facilities have been provided for designers to modify model parameters more quickly without any change to the initial concept. Using parametric design methods in modelling is an appropriate method to find the optimum solution. The significance of exploring concepts by combining a parametric daylight device design with a façade system has been proposed. According to the literature, some research interests to develop this idea from architecture and engineering points of view, such as:

- What is the type of façade system?
- What is the effect of daylight strategies in building design process?
- What is the type of daylight device components?
- What is the parametric modelling and dynamic process in design?

The focus of this research is on simulation and analysis of daylight performance to find the optimum solution for buildings with respect to parametric design. Designers use different methods to analyse daylighting in buildings. Though the climate based method is considered one of the best options to analyse the daylighting. Daylight availability in climate based method is effective to determine glare. The façade and daylight device system for two different case studies have been redesigned using Rhino software. Where Grasshopper plug-in has been employed for parametric design and DIVA plug-in is used for daylight simulation.

This research wills therefore the daylight assessment of new forms regarding to parametric modelling and newest daylight analysis to improve the human comfort space.

Chapter 3: Research design

3.1 METHODOLOGY

This research presents a method for optimizing the design of façade system devices to control daylighting performance in buildings and can be divided into three main sections which will be described as follows:

1. Model development
2. Project study design
3. Experimentation and Evaluation (Optimization)

3.1.1 Model development

This research is based on two case studies that assessed the state of daylight device components on façade system. The model was developed on the following:

a) Existing daylighting strategies in buildings; specifically state of the art in innovative daylighting devices, including openings, light guiding systems and light transport systems

b) Building skins; traditional designs (i.e. double skin facades) and new parametric designed skins

c) Case studies assessment of parametric designed skins; the current integration of daylighting solutions into parametric design skins the benefits, and limitations of current designs to inform the development of new design criteria (Step 2)

d) Simulation and modelling software; search and assessment of simulation and modelling software including parametric modelling packages such as Rhino and Grasshopper, and lighting simulation tools such as Radiance.

e) Define the building type to be investigated to define the practical purpose of the skin and the needs in terms of daylighting.

A design criterion based on the literature review, case study analysis and requirements for tropical and subtropical climates have been developed in this step.

The design criteria will be used implemented in the design of a new integrated solution for an organic building skin.

3.1.2 Project study design

This step involves the design of an innovative organic form that integrates daylighting strategies in the building skin based on the criteria develop in the model development search involves the use of sophisticated geometric analyses, performed by the parametric modelling software called “Grasshopper”. This software has a good graphical algorithm editor that enables designers to generate parametric forms. Both the Rhinoceros and Grasshopper software are widely used and popular among students and professionals, in both traditional and parametric design (Lagios, Niemasz et al. 2010).

3.1.3 Experimentation and Evaluation (Optimization)

The next step assesses daylighting performance. DIVA plugin in Rhino and Grasshopper software is explored for the daylighting performance of different solutions. DIVA contains Radiance, a suite of programs for the analysis and visualization of lighting in design. It is used to predict illuminance, visual quality, and appearance of spaces and evaluates new lighting and daylighting technologies. This approach facilitates the visualization of lighting effects through any particular space. The testing process will be continuous and the results will be used to improve the design in step 2. This process will be repeated until a satisfactory outcome is achieved.

3.1.4 Concept map

The method has been summarized in Figure 3.1 and serves to provide optimize daylight device positions on the façade system to control daylight performance in building. This research has five parts such as definition of problem, literature review, project study design, experimental and evaluation of the optimize design process concerning daylight performance.

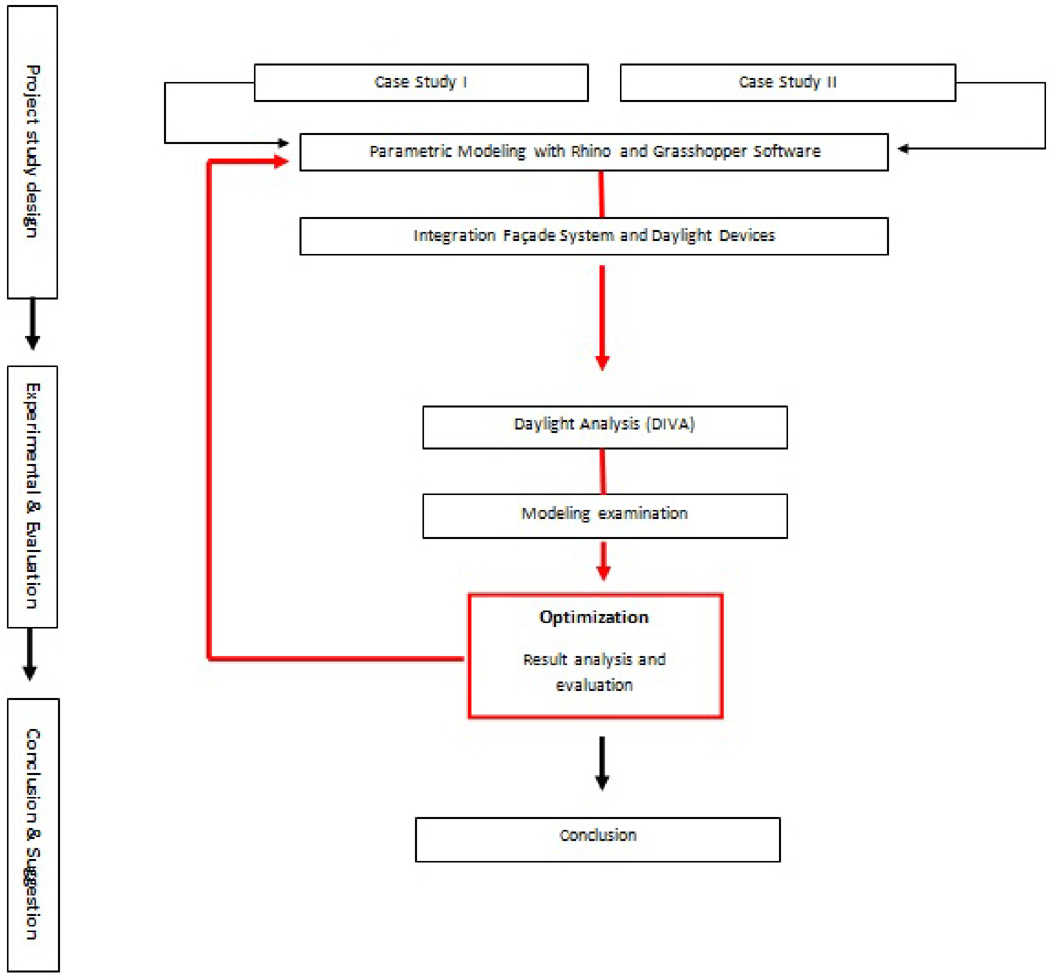

Figure 3.1. Concept map.

3.1.5 Analysis tools

Rhinoceros is one of the most well-known software for the creation of three dimensional NURBS models based and free complex modelling (Reinhart and Wienold 2011). NURBS geometry is a mathematical representation that can accurately define any shape, line or surface. This software has a model analysis capability and exports data to CNC[3] machine (Tedeschi 2011). Rhino software has been employed and the two different plugs-in were:

- Grasshopper plug-in (geometry design)
- DIVA plug-in (daylight analysis)

[3] computer numerical control

Grasshopper plug-in (GH)

The Grasshopper Plug-in operates associating parts geometry created within the Rhinoceros software or created by de novo with a graphic editor (Lagios, Niemasz et al. 2010). GH plug-in has been developed for designers and engineers to create a new form by using generative algorithms and associative modelling techniques (Tedeschi 2011).This plug-in is a suitable environment for architects and engineers to generate three dimensional models in a flexible way, to control the design process and "*allows the development of script without any programming knowledge"* (Tedeschi 2011).

DIVA Plug-in

The DIVA plug-in, designed for Rhinoceros, evaluates the daylighting performance at each point of the design space. DIVA uses the base programs Radiance and Daysim, which are suitable for the analysis and visualization of lighting in design (Jakubiec and F.Reinhart 2011). Radiance is the gold-standard software for daylighting and light assessment. Daysim is an associated program that enables Climate-Based Daylight Metric (CBDM) and is employed to predict illuminance, visual quality, appearance of spaces and to evaluate new lighting and daylighting technologies (Reinhart and Wienold 2011). However, DIVA analysis thermal load simulation as the Energy Plus and contains the Radiation Maps, Photorealistic Renderings, Climate-Based Daylighting Metrics, Annual and Individual Time Step Glare Analysis, LEED and CHPS Daylighting Compliance, and Single Thermal Zone Energy and Load Calculations (Nimasz 2012). DIVA with DAYSIM and Energy Plus calculate the annual hourly illuminanace values and high light metrics. This study used DIVA plug-in to simulate effect of façade components such as daylight system on daylight performance regarding to newest daylight metric (climate-based). This plug-in have a good relationship with GH and Rhinoceros software to calculate daylight simulate.

Simulation in a DIVA environment is organized from a toolbar integrated in Rhinoceros and GH plug-in interface as shown in *Figure 3.2*.

Figure 3.2. DIVA plug-in toolbar in Rhinoceros software and Grasshopper plug-in[4].

DIVA Daylight Analysis for Rhinoceros

DIVA in the Rhinoceros interface comprises four buttons[5]:

- Location (Project Info)
- Nodes
- Material
- Metric and parameters

Location (Project Info)

The first button "Project Info" allows the user to select a TMY weather file[6] (geographic project location) and File naming for all DAYSIM and Energy Plus simulations (*Figure 3.3*) (Lagios, Niemasz et al. 2010; Jakubiec and F.Reinhart 2011).

Nodes

This plug-in serves to analyse daylighting after selecting a surface or surfaces and asks the user to put the "Nodes" on the face. The Nodes are series of sensor points arrayed across that surface or surfaces to receive the natural light. (Lagios, Niemasz et al. 2010).

Material

This button can assign predefined Radiance materials to each layer and can add two different material libraries, like daylight material and thermal material to the main file (Nimasz 2012).

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[4] Available from http://www.rhino3d.com/
[5] Available from http://diva4rhino.com/
[6] Available from http://apps1.eere.energy.gov/buildings/energyplus/

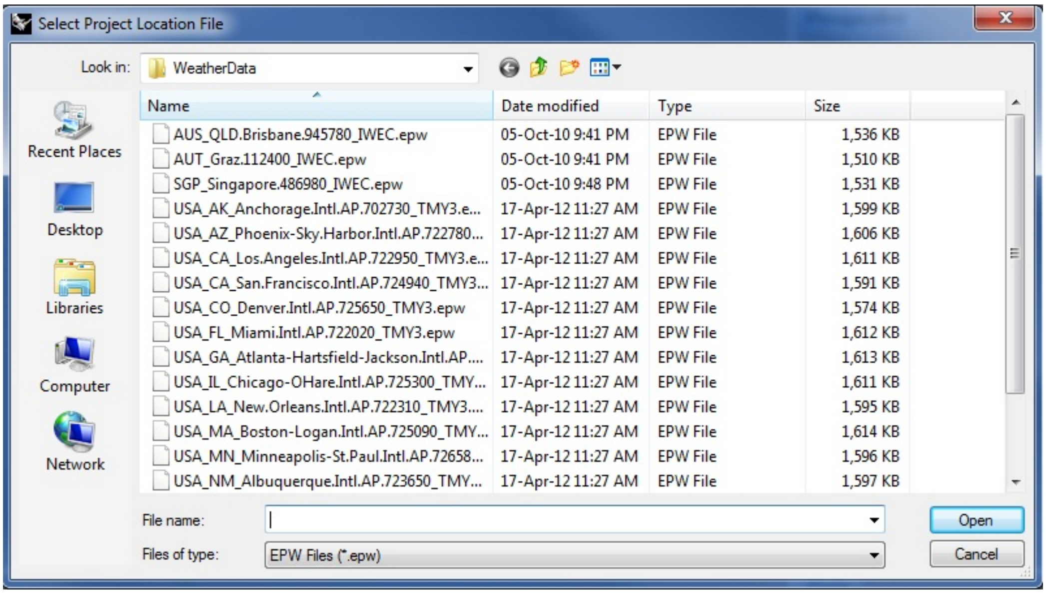

Figure 3.3. Add TMY weather file from Energy plus simulation software web[7].

Metric and parameters

The last button asks the user to define five Radiance parameters (*Table 3.1*). The Radiance simulation parameters used for all simulations were ambient bounces (ab), ambient divisions (ad), ambient sampling (as), ambient accuracy (aa) and ambient resolution (ar)(Reinhart and Wienold 2011). “Metric” provides three choices to test run the given model: daylight images, daylight grid-based and thermal single-zone. However, daylight images and daylight grid-based used a different type of simulation[8]:

Daylight image

- Visualization
- Time lapse
- Radiation Map
- Point in Time Glare
- Annual Glare

Daylight Grid-Based

- Daylight Factor
- Point in Time Illuminance

[7] Available from http://apps1.eere.energy.gov/buildings/energyplus/
[8] Available from http://diva4rhino.com/

- Climate Based
- Radiation Map

Table 3.1 Radiance simulation parameters sample[9] (Reinhart, Mardaljevic et al. 2006)

ab	ad	as	aa	ar
2	1000	20	0.1	300

DIVA Daylight Analysis for Grasshopper Plug-in

DIVA for Grasshopper interface comprises three main Components:

- Geometry With Material Assigned Component
- DIVA Daylight Analysis Component
- Legend

The DIVA platform for Grasshopper assembly extends the DIVA for Rhino tools to the generative modelling program Grasshopper and daylight analysis in a parametric software environment. The final results from DIVA in Grasshopper are presented with the below percentage of daylight occupied.

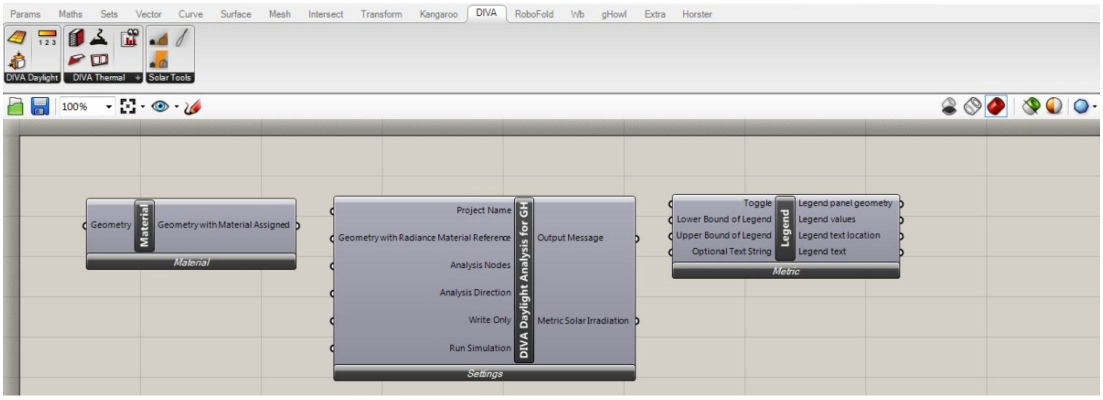

Figure 3.4. DIVA daylight analysis components in Grasshopper plug-in[10].

3.2 REDESIGN CASE STUDIES

The effect of integration envelopes façade systems with daylight devices on daylight performance were examined via two case studies the Esplanade building and Kunsthaus Graze. Redesigning daylight devices and façade system with new

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[9] Available from http://diva4rhino.com/
[10] Available from http://www.grasshopper3d.com/

software and methods (such as parametric modelling) could be effective for architects and engineers to optimise design and re parameterize modellings to find the best solutions such as sustainable design. This research present two case studies, based on the geometries of the Esplanade and Kunsthaus to explore the parameters of shading panels and nozzles on the façade system, and the effect of components on the natural light performance in the interior space. Accordingly, this section introduces the case studies and explains how designers can be redesigned with Rhino software and the GH plug-in to find the parametric process or algorithm design.

3.2.1 Case study 1

The Esplanade buildings on the bay project were design by Michel Wilford and Partners in 2002[11]. The building is located in Singapore at latitude 1.29° N and longitude 103.9° E. In this case study, the cladding façade system was used to control daylight performance in the building (*Figure 3.5*).

*Figure 3.5.*View of Singapore Esplanade[12] (the Theatre (left) and Concert Hall (right)).

The surface system comprises three main parts; costume designed space trusses (triangular top chord grids) to modify the free form surface, glazing surface system

[11] Available from http://designalmic.com/esplanade-theatres-on-the-bay-michael-wilford-partners-dp-architects/
[12] Available from http://chris-skyline.blogspot.com.au/2012/03/esplanade-theaters-on-bay.html

and aluminium shading elements (Gore 2002). The architect and engineers face two major design challenges:

- Adjustment method of the shading panels to meet aesthetical and functional needs
- How to produce, transport and erection different building components

Form finding with software potential

The claddings of both buildings were designed with NURBS[13] surface. Coons and Bezier developed the theoretical NURBS and implemented this into the CAD programs[14] to design Singapore's Esplanade envelopes.

Cladding System

The cladding façade system was used in this case to control daylight performance in the buildings. The glazing envelope and distinctive aluminium shades were each on a metal grid on the exterior face. The façade of the Theater and Concert Hall were covered with 4,900 panels, each consisting of 4mm aluminium sheets. The architect group examined a proposal of triangular/ half pyramid sunshades distributed in a vertical arrangement along the sides of the glass surface (Gore 2002). Designers used different shading sizes to control the daylighting and glare probability in the interior space. The design of the cladding surface had to manage the contrast between the outside view from the inside, as well as control the direct sunlight coming into the buildings from the exterior (Ltd 2004). The shading size and formation of the devices depended on their location from the sun path had different position. Based on the sun path in Singapore, the designers used long, large and small sunshades on the exterior surface (*Figure 3.6*).

The daylight system for the Esplanade buildings was the most important aspect of this project. The shading devices covered the whole at building surface to control the daylight. London-based structural engineers Atelier One and Environment engineers Atelier Ten were selected to design and research the cladding tools for this project. The overall shape of the shading system went through a series of

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[13] Non uniform rational Beta splines can represent 3D geometry
[14] Available from http://en.wikipedia.org/wiki/Pierre_B%C3%A9zier

optimization methods, to satisfy both natural lighting and thermal transfer requirements (Gore 2002; Ltd 2004).

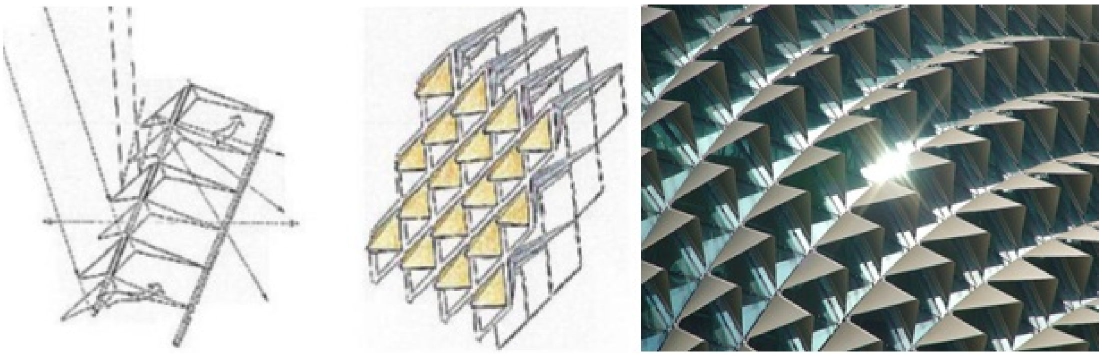


Figure 3.6. North and South Facades of Singapore’s Esplanade Building (Gore 2002).

Design and Calculation

Wilford and Partners are followed three steps, the first being the bearing concept to stabilize of the façade structures and support the lower and upper edges of the space frames. The second part of this project is the evaluation of loads, specifically dead loads, wind loads, live loads, installations and thermal loads. Engineers used the Wind Tunnel tests at the City University of London to obtain the wind for thermal loads calculation pressure coefficients for the envelopes. The last step calculated the deflections, member forces/ reaction and dimensioning (Gore 2002; Ltd 2004).

3.2.2 Redesign cladding system in the Esplanade Theatre Building with Grasshopper plug-in (GH)

This section presents the three steps used to redesign the cladding system in the Esplanade buildings and redesign shading devices with parametric modelling (using GH plug-in) to find the optimum device position (appendix A).

I. Glazing surface design

The Esplanade Theatre building shape is like an Oval and the design of this form in GH plug-in used two circular tubes for the top and bottom to design the glass panes on the cladding system. However, the glazing surface in this case was redesigned to find positioning of the shading devices and control the glare potential in interior space, Glazing surface were divided in to eight parts (*Figure 3.7*), and each part includes glass panes, the basic structure and shading devices to find the optimum device positions.

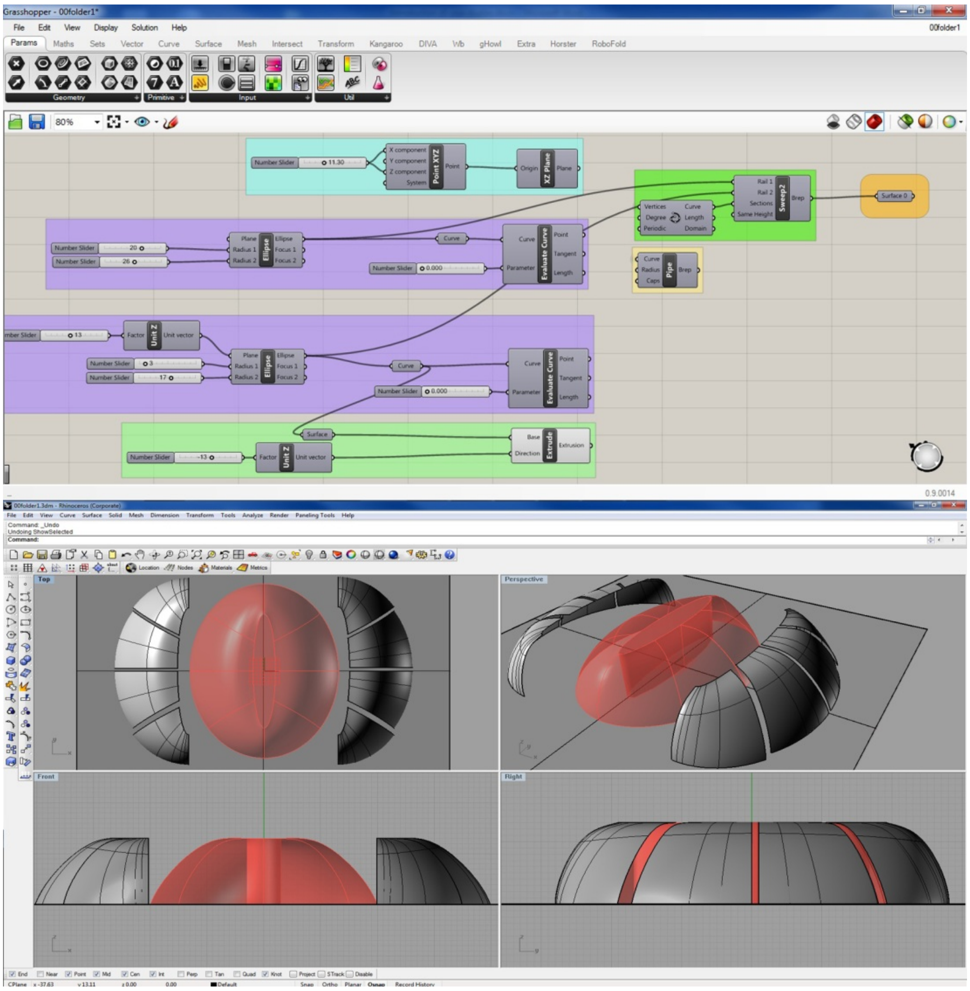


Figure 3.7. Design of glazing surface in GH plug-in.

II. External grid structure

The external grid was designed on the glazing surface to established daylight devices on the façade system. The control points of a NURBS surface used to parameterize the overall grid structure on the surface. Also, each part of the surface structure used 140 rectangles of approximately 20 x 20 mm to control the daylight devices on the façade system (*Figure 3.8*).

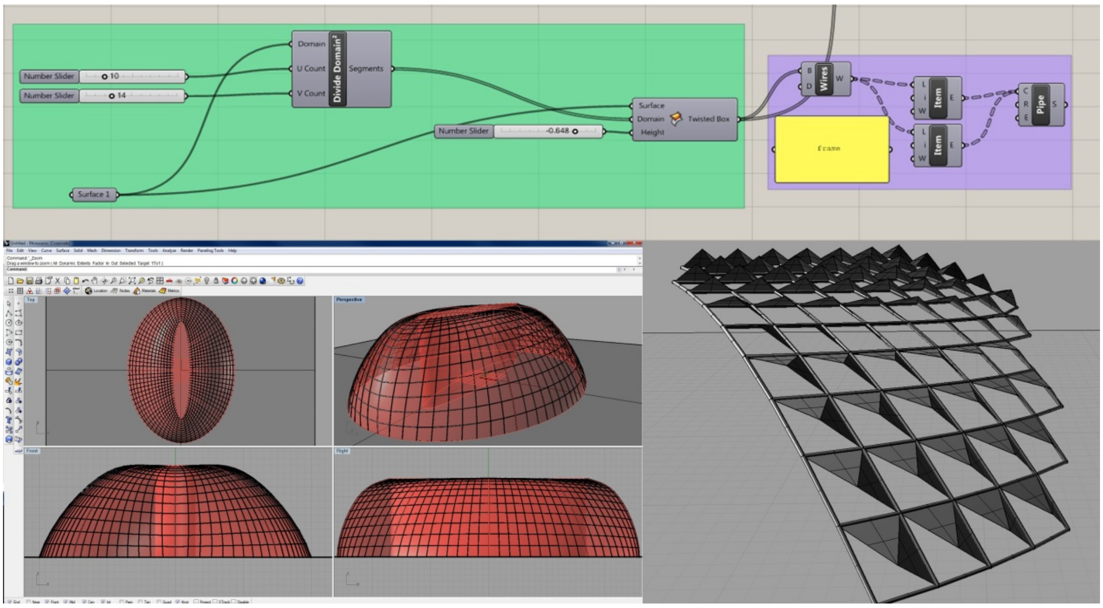


Figure 3.8. External grid structure design in GH Plug-in.

III. Shading devices design

The overall shape of the shading envelope is of a pyramid. This section describes the three steps to redesign the pyramid forms of the shading devices on the Esplanade cladding system (Figure 3.9).

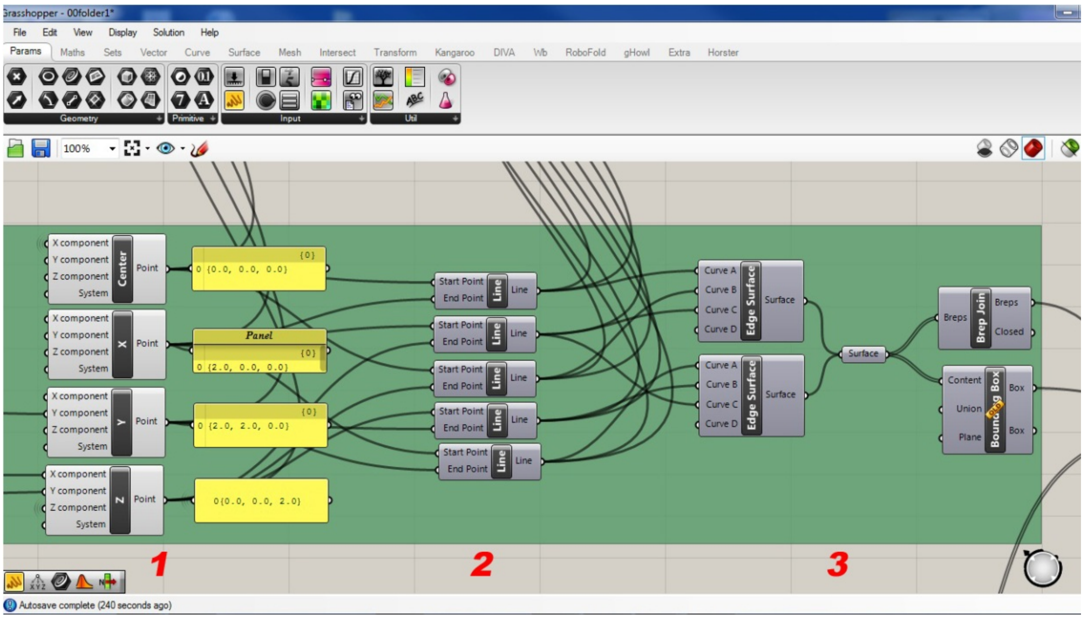


Figure 3.9. Shading system parametric process.

Step I. Find main points on the device

This geometry is organized with four cardinal points on the XYZ vectors to model the shading devices. The first point presented in (0, 0, 0) and the X and Y point coordinates are (2, 0, 0) and (0, 2, 0). The apex point coordinate (1, 1, 2) is located on the Z vector (Figure 3.10). Parameters in each point are variable from 0.25m to 2.00m to find the optimum position. Also, the Z point in this geometry is a main parameter to identify optimum device position in this case. On the other hand, the *number slider*[15] has been used with the GH plug-in to control parameters such as defining the values of coordinates. The next step is to set the multi numbers to show the coordinate geometry in the Rhino environment, and add the line component to redesign the shading edge structure. The maximum edge dimensions of the shading devices are 2.00m (Figure 3.11).

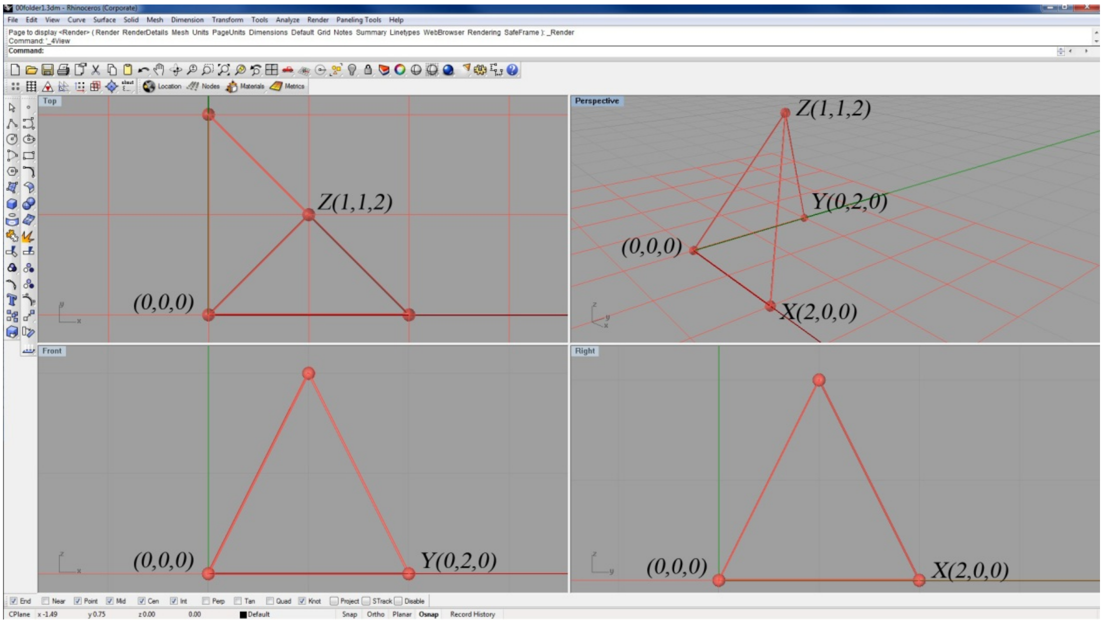


Figure 3.10. Coordinate on the XYZ vector.

[15]Available from www.grasshopper3d.com

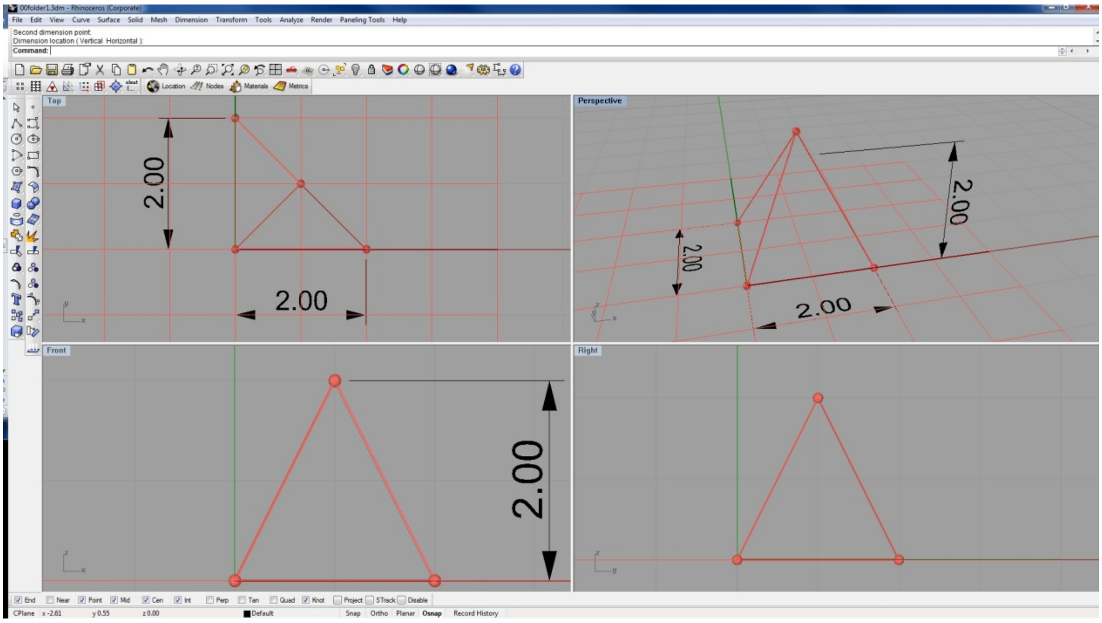


Figure 3.11. Shading device dimension.

Step II. Connection frame between cardinal points and edge design

The structure of the geometry has been parameterized to control cardinal points on the devices, regarding to the U and V coordinates (*Figure 3.12*). Used the *line component* [12] to connect cardinal point to the points is useful for design the device structure frames in this section.

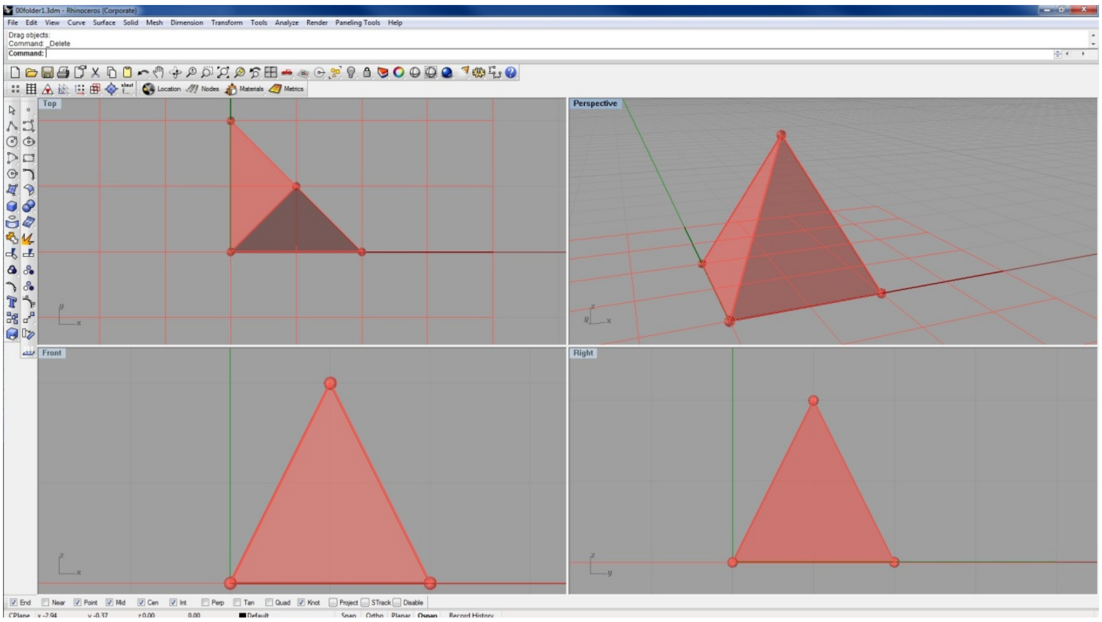


Figure 3.12. Design edge surface for daylight devices with line component.

Step III. Integration open able daylight device

Device opening is defined as the distance between (0, 0, 0) and the coordinate of the apex. Therefore, moving the apex coordinate along the line x=y (bisector of xy) means the device opening changes. Find the optimum opening position from Z direction on the cladding system , means controlling the apex with *number slider* from 0.25m to 2.00m (open and close opening) (Figure 3.13). *Bounding Box*[4] and *Rotate* Components have also been used in this case to rotate the daylight devices according to the XYZ vectors on the grid structures.

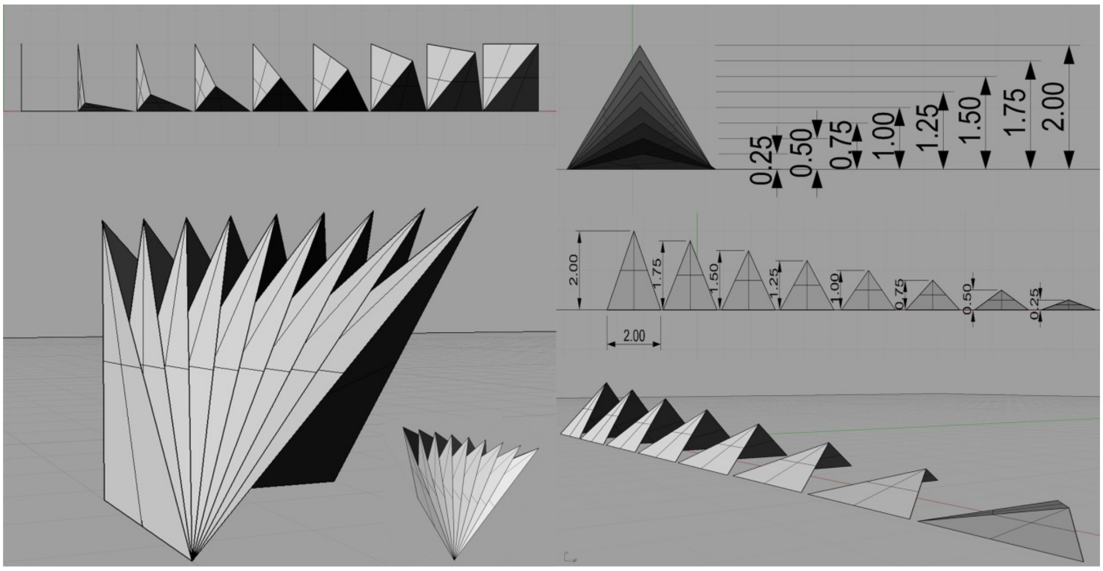


Figure 3.13. Control apex point coordinate for devices with Number slider from 0.25 to 2.00 m.

3.2.3 Case study 2

The Kunsthaus Graze, an exhibition hall designed for international exhibitions in Graz, Austria (47 ° N, 15.40° E), was design by Peter Cook and Colin Fournier and completed in 2003. The Kunsthaus volume has a complex free form and was difficult to designer to finding free form modelling from the structure (Bogner, Cook et al. 2004). The surface of this building has been cover by a triangular brace panel system, hexagonal ports where each panel is covered with Plexiglas (*Figure 3.14*). The structure of the top level of this building used a steel frame in the skin for design a dome on the main hall. The facade skin design in this case incorporates the nozzles (Cook and Fournier 2004). Nozzles were integrated with the façade system to transfer natural light into the exhibition hall from the north side of the building. The nozzles were based on heritage design as in the Old Clock Tower in Graze (Lefaivre 2004).

3.2.4 Redesign nozzles on the Kunsthaus Graze façade system with Grasshopper plug-in (GH)

Use of the GH plug-in is applicable to redesign and analyse devices such as nozzles in the Kunsthaus Graze building (Appendix D). This step described the redesign of the nuzzle to optimize parameters and control the device positions such as height variations, opening and closing upper apertures and nozzle rotations from the north. The base form of the Kunsthaus Graze facade is a complex free form, illustrated in this case with Rhino software to redesign the surface and combine nozzles with the façade (*Figure 3.15*).

Figure 3.14. Façade system incorporate the nozzles for bringing daylight to top level of Kunsthause Graze (Cook and Fournier 2004).

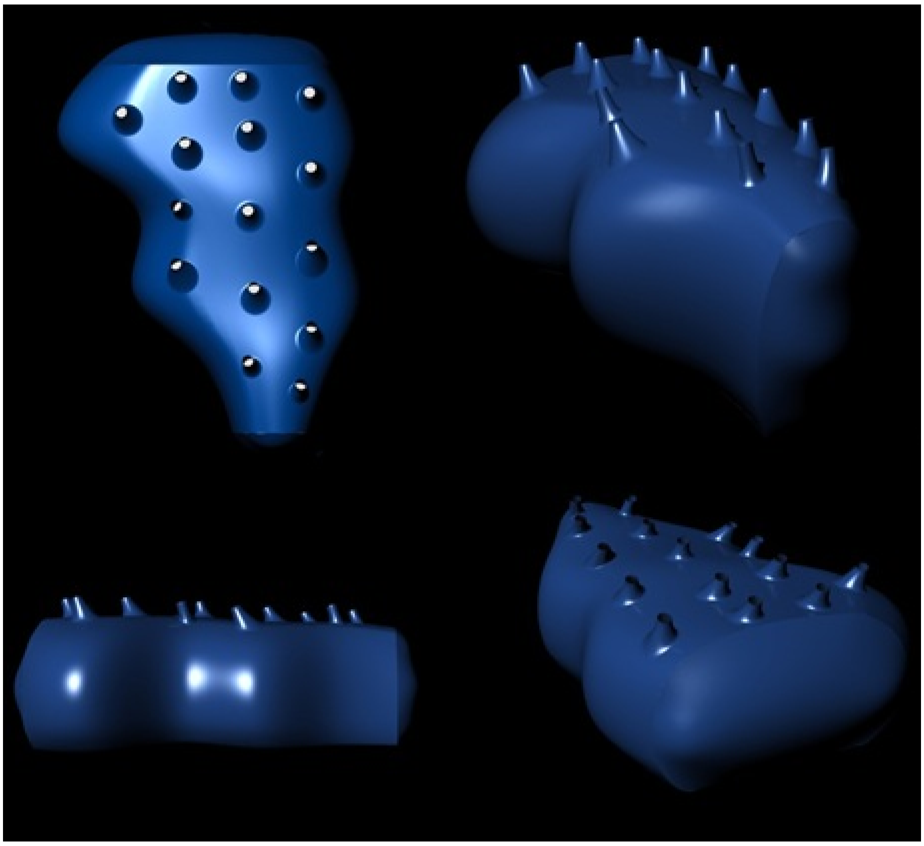
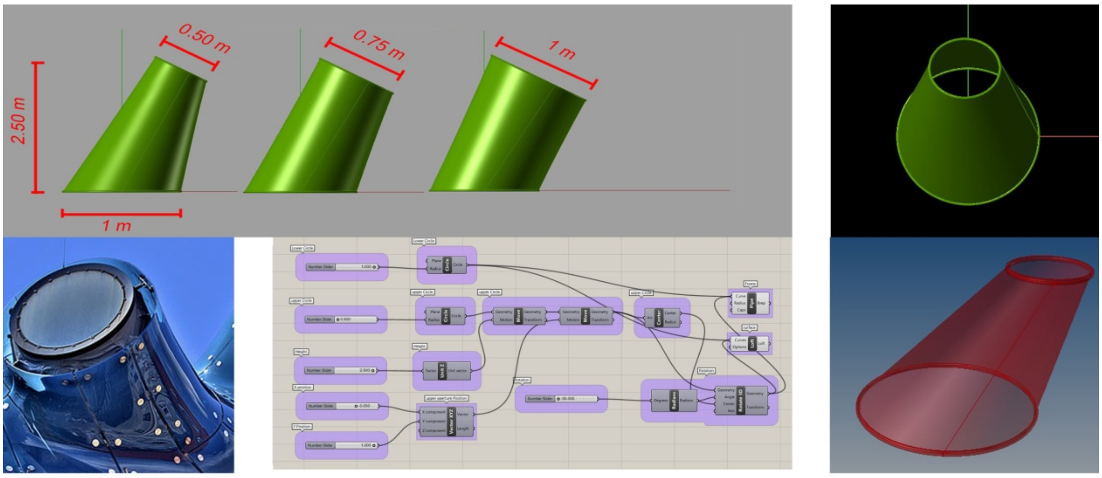


Figure 3.15. Redesign kunsthaus Graze free form geometry with Rhino software.

Based on the real building variation of nozzles such as lower and upper aperture opening, height and rotations have been fixed. However, in this model the upper aperture variation and nozzle rotations have been changed to find the optimum device position on the façade system (*Figure 3.16*). For instance, two circle components were used to control the upper and lower aperture such as opening and closing nozzles. The lower circle has been fixed on 1m radius and upper circle aperture is variable from 0.5m to 1.00m. Height of the nozzle geometry in this model was located 2.50 m from the centre point of each lower circle for most nozzles. The GH plug-in enable a 3D rotation on and move components have been used to rotate nozzles from the north. Therefore to rotate nozzles from the north, the centre point of the upper aperture in most nozzles were controlled with the number slider and 3D rotate components.



Device *Parametric process in Grasshopper* *Grasshopper Modeling*

Figure 3.16. Parametric process in GH plug-in k to redesign nozzles in Kunsthaus Graze.

3.3 COUNCLUSION

This section described and redesigns two case studies based on the geometry of the Esplanade building in Singapore and Kunsthaus Graze in Austria to explore the daylight device parameters (such as shading panels and nozzles) on the façade system to analyse effect of components on the natural light performance in the interior space. Firstly, the case study buildings are modelled by parametric modelling plug-in called “Grasshopper” (GH). Secondly, through experimentation and evaluation daylight performance is assessed. The GH plug-in is used with Rhinoceros for parametric modelling. Parametric modelling is used to adapt the components on the façade systems and examine daylight device aperture to analyse functionality, and effect on daylight performance in buildings. The DIVA plug-in, also designed for Rhinoceros, evaluates the daylighting performance at each point of the design space. DIVA is suitable plug-in for the analysis and visualization of natural lighting in this study. In chapter 4 all daylight results from DIVA plug-in is examined.

Chapter 4: Results

This chapter presents the results of the climate-based daylight metric simulations using DIVA and GH plug-in. The climate-based metrics used for the analysis include Useful Daylight Illuminance ($UDI_{100\text{-}2000Lux}$), $UDI_{<100Lux}$, $UDI_{>2000Lux}$ and Daylight Availability (DA_V). The chapter presents the results obtained for two case studies based on the Esplanade building in Singapore and Kunsthause Graze, in Austria. The aim was to find the optimum annual daylight levels, with reduced probability of occurrence of glare and/or insufficient light levels (under 100lux).

4.1 ESPLANADE THEATRE DAYLIGHT ANALYSIS AND OPTIMIZATION

For the design optimization process, this research assesses daylight performance using the three metrics: UDI $_{100\text{-}2000lux}$, $DA_{V200lux}$ and Glare Probability. This study of the case study base on the Esplanade Theatre, evaluated two approaches to find the optimum daylight performance in this case study. The approaches are:

- Variation of building orientation from the north to find optimal orientation
- Variation of the projection of the daylight device on the façade system to find optimal dimension

Building orientation was the initial variable in the design process and is the most important parameter to consider for the design of a building with passive thermal and visual comfort (Krüger and Dorigo 2008). To measure the orientation in buildings, looking to azimuth angle of the surface from the north is necessary (Steemers 2002). Building rotation is one way to maximize the daylight comfort in the space. Therefore this case study is rotated four times from the north (0^0, 45^0, 90^0 and 135^0) to assess the effect of orientation in daylight performance (*Figure 4.1*). In addition to the building rotation variation, shading devices were opened and closed to obtain the best light permeability from the device positions on the façade system.

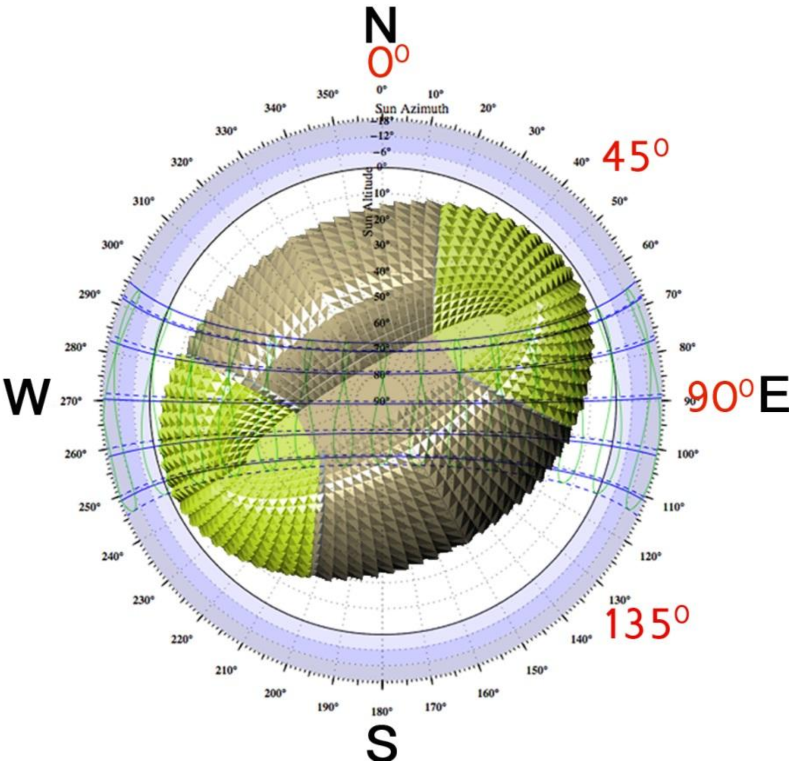


Figure 4.1. Building rotation from the north to the south (Singapore sun path).

Moreover, the daylight devices were modified to obtain the best device arrangement on the façade system. The shape of the devices was controlled by sliders in the GH plug-in to find the optimum projection of the daylight devices. The projection of daylight devices have been changed in nine steps from 0 to 2.00 m for each building orientation to find the optimum natural light inside the building and optimum device position on the façade system (*Figure 4.2*). For this study, and base on the real building, shading devices on the side of the building have been fixed on 2.00 m (shadings highlighted in brown in *Figure 4.1*) and projection of the daylight devices at the ends have been vary from closed (2.00 m projection) to maximum aperture opening (0 m projection). On these sections of actively varied daylight devices are highlighted in green. Variation in building rotation and daylight device projection were conducted in parallel to assess the visual comfort and optimum daylight performance in the interior space.

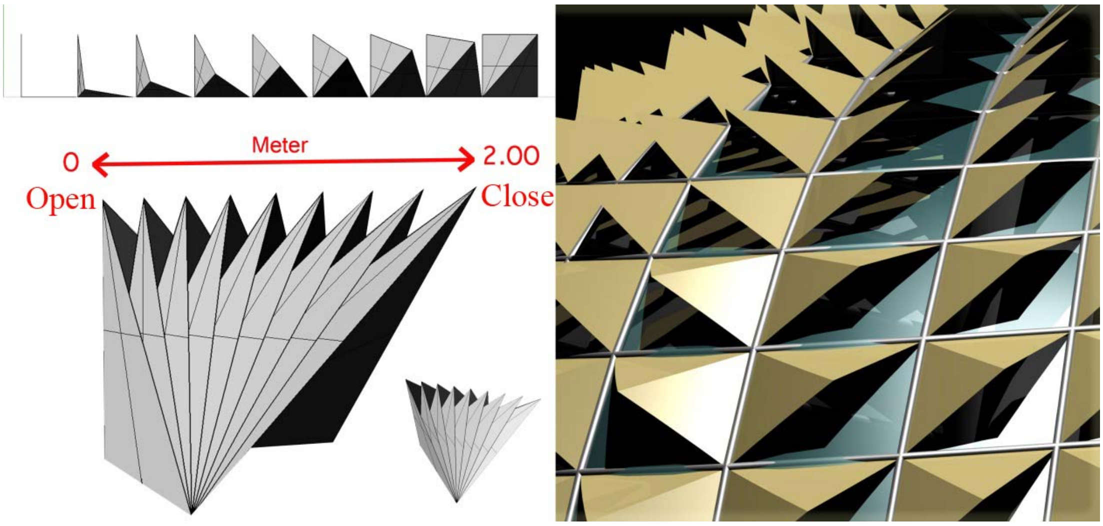


Figure 4.2. Variation of daylight device projection on the shading system.

The material surface reflection can change the result of the design performance. Therefore assigning material descriptions to the substrate geometry of surfaces was an essential aspect in accurately modeling the performance of each skin system. The materials which have been assigned to the surfaces are selected based on standardized reflectivity (*Table 4.1*). The following table is a list of the assigned materials and their reflectivity.

Table 4.1. Material surface properties

Components	Reflectivity	Transmission
Cladding surface	35%	_
Glazing	_	65%
Interior walls	50%	_
Floor	20%	_
Outside facade	35%	_

4.1.1 Useful Daylight Illuminance 100-2000 lux Analysis ($UDI_{100-2000lux}$)

UDI $_{100-2000lux}$ analysis is the initial step to assess the performance of natural light in the case study building. Within DIVA plug-in the annual percentage of the useful daylight illuminance (100 to 2000 lux) per sensor (1384 sensors are placed on the measuring grid at 0.85 m above the ground floor) is calculated using a Weekly 8am to 6pm occupancy file. The horizontal axis in *Figure 4.3* shows the degrees of building rotation from the north while the vertical axis shows the percentage of time throughout the year the horizontal illuminance due to daylight is between the 100 to 2000 lux brackets. This figure also illustrates with the colour lines the variation in daylight from the different device projections (from 0.00 to 2.00 m). In this study, values for $UDI_{100-2000lux}$ higher than 60% are considered a good performance for the daylighting strategy. It means that each sensor during the simulation achieved a UDI between 100-2000 lux 60% of the time. However, for Glare probability, the aim is to reduce the occurrence of glare. Due to the activities performed in this space (exhibition) a glare probability of 30% is acceptable. *Figure 4.3* shows the maximum UDI $_{100-2000lux}$ is about 87-90% which is obtained for device openings of 1.75 m and 2.00 m. Also device opening of 1.5 m is located on the cut-off line (70%). Projections with opening values of 1.75 m, to 2.00 m have a percentage of UDI which does not change for the different building orientations. Moreover, the lower percentage UDI $_{100-2000lux}$ (achieved) of 56-38% is obtained for the devices with the most open projection. Orientation does not seem to affect the results for these projections. When the projection of daylight devices are 2.00 m, 1.75 m and 1.50 m 70-90% UDI $_{100-2000lux}$ is achieved for most building rotations. In contrast, when the daylight device projection varies from 1.25 m to 0 m, UDI percentages range from 56-38% due to the space being over light. *Figure 4.4* clearly shows how the percentage UDI is reduced and falls under the 60%, when the daylight device projection is smaller than 1.25m, and the drop from 2m to 0m is 60%. For example, after closing the daylight devices from 1.00 m to 0 m, $UDI_{100-2000Lux}$ reduces 10% (Appendix B). Finally as building orientation does not seem to have an effect in the annual occurrence of useful daylight levels in the building a further assessment was conducted using $DA_{V200lux}$ to analyse daylight comfort in the space.

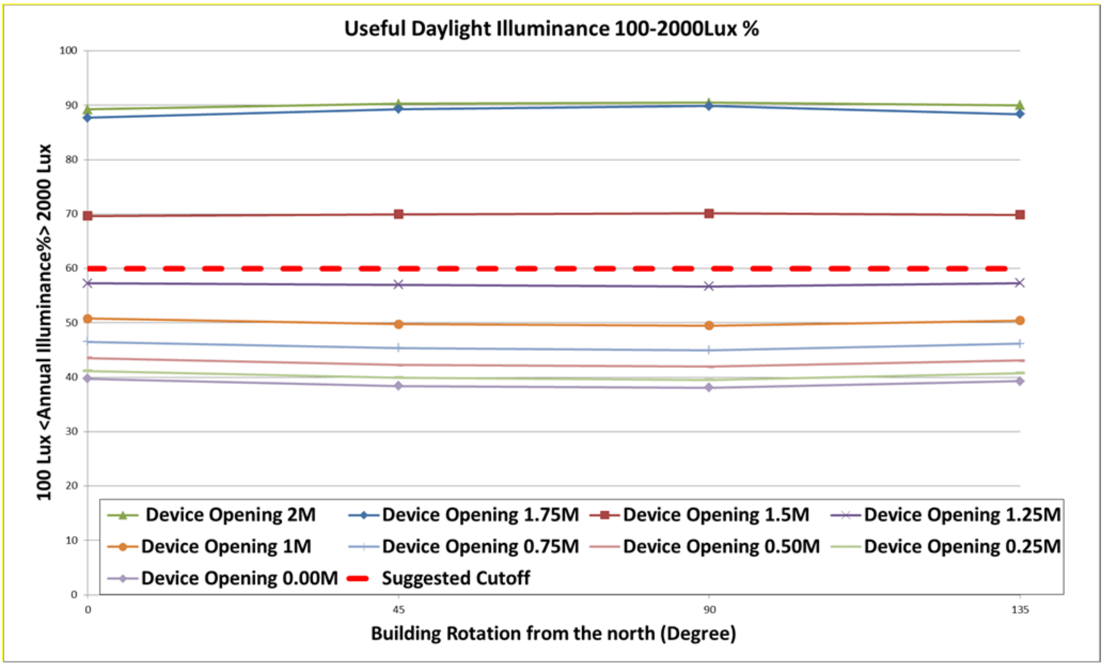


Figure 4.3. Useful Daylight Illuminance $_{100\text{-}2000\text{Lux}}$ regarding device projection.

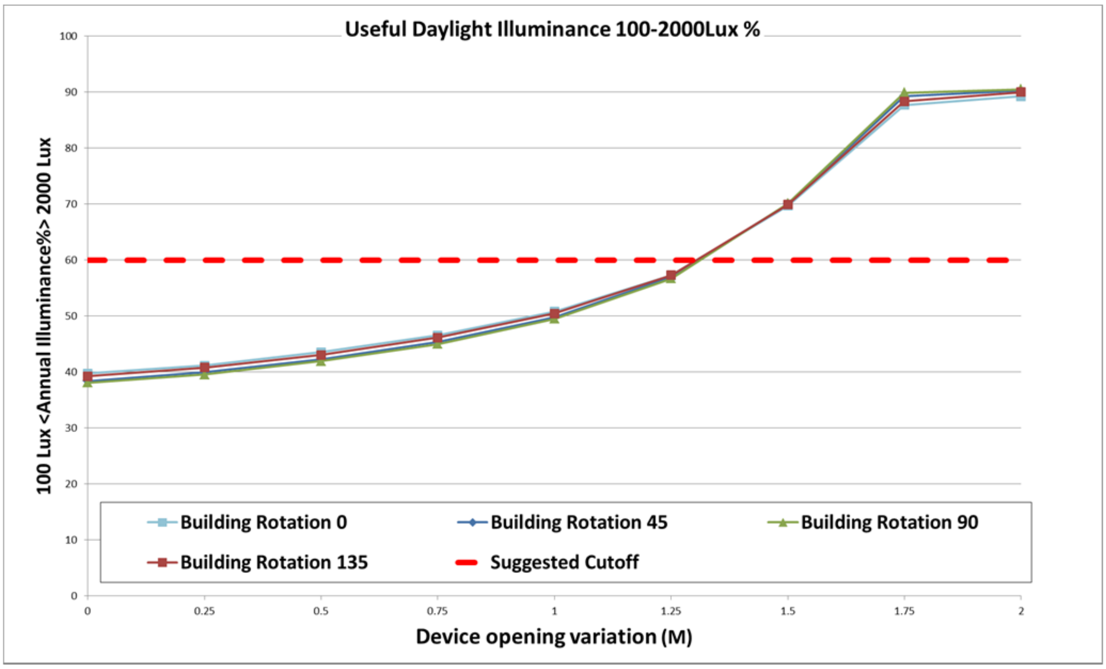


Figure 4.4. Useful Daylight Illuminance $_{100\text{-}2000\text{Lux}}$ regarding building rotation.

4.1.2 Useful Daylight Illuminance fell short (UDI$_{<100\text{Lux}}$)

UDI fell short, explained earlier as the percentage of time that average illuminances fall under 100lux, can also be calculated and use to evaluate the performance of the different designs. In this case lower percentages of UDI fell short would mean better performance of the daylight devices. *Figure 4.5* illustrates how UDI fell short varies in the Esplanade building, when device variations and building orientations are changed. The simulation demonstrates that when daylight device variations closed from 0 m to 2.00 m, UDI $_{<\ 100Lux}$ percentages increased for most building rotations (0^0, 45^0 and 135^0). For example, the lowest percentage of UDI $_{<\ 100Lux}$ (2%) was obtained, when the daylight device projection is 0 m and the building location rotated 45^0 from the north. Also, in same building location rotated (45^0) the highest percentage of UDI $_{<\ 100Lux}$ (9.5%) was then achieved when the daylight device projection is 2.00 m. When varying the projection of daylight devices reducing from 1.50 m to 0 m, the illuminance level was less than 5% of the sensors in most building rotations, but the glare probability was significant for these daylight device variations as shown later in the glare probability study (Section 4.1.4). These results are illustrated in *Figure 4.6* so that when the closing projection of daylight devices are 1.25 m, 1.50 m, 1.75 m and 2.00 m, 3.5-9.5% UDI $_{<\ 100Lux}$ are achieved for most building rotations. A reduction in the variation of device projection from 1.00 m to 0 m in for each building rotation, the percentage of UDI fell short decreased from 3 to 2. Regarding to UDI $_{<\ 100Lux}$ analysis device projection from 0 m to 1.75 m are slightly better than 2.00 m.

Consequently the percentage of UDI fell short is not significant for most daylight device projections from 2.00 m to 0 m and building rotations. The simulations show that less than 10% of the sensors (from 1384 sensors are placed on the measuring grid) achieve lighting levels less that 100lux throughout the year.

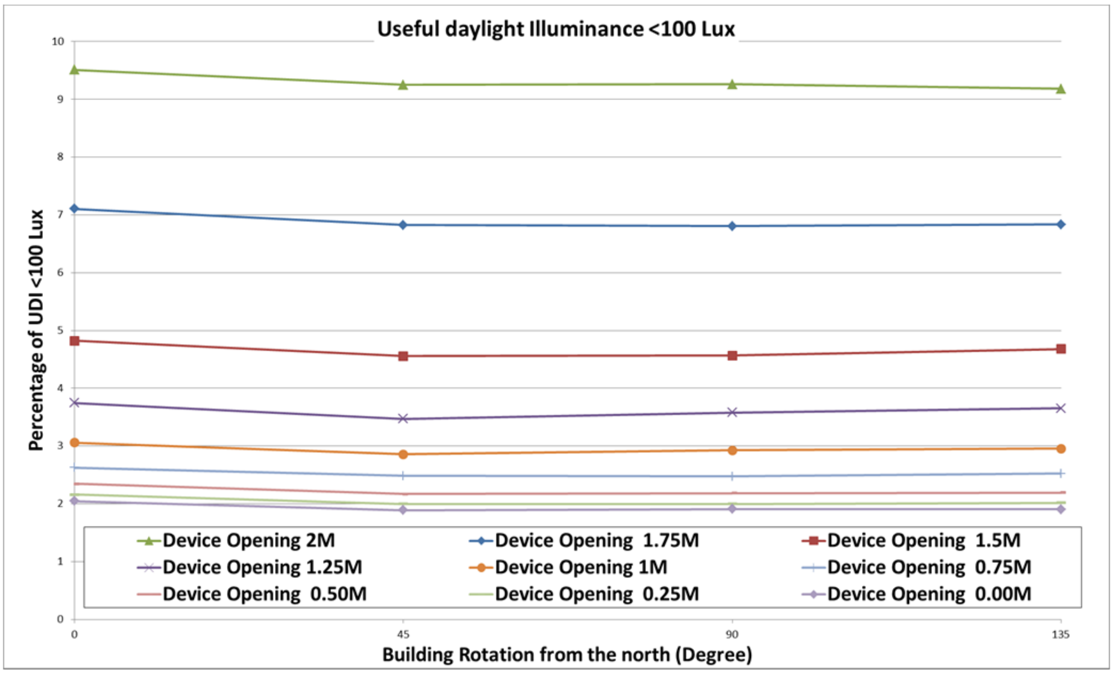


Figure 4.5. UDI fell short regarding device projection.

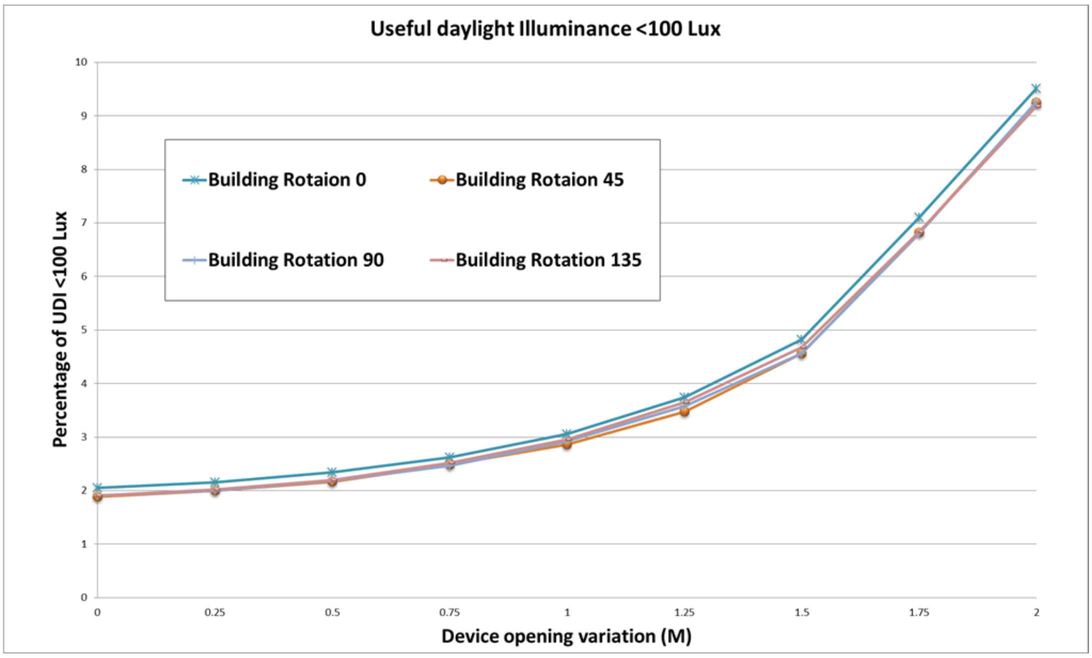


Figure 4.6. UDI fell short regarding building rotation.

4.1.3 Useful Daylight Illuminance exceeded ($UDI_{>2000lux}$)

DIVA plug-in calculates UDI exceeded in daylight simulation, when sensors on the floor achieved illuminances higher than 2000lux. This analysis identified that the building rotation when changed from 0^0 to 135^0, four daylight device projection 0 m, 0.25 m,0.50 m, 0.75 m, 1.00m, 1.25m are obtained $UDI_{>2000lux}$ from 40% to 60%

(*Figure 4.7*). For instance when the daylight device projection is 0.50 m, 55% UDI exceeded is achieved for a building rotation 90^0 from the north. Unlike the previous example in same building orientation (90^0) when the variation of device projection changed to 1.75 m, the percentage of $UDI_{>2000lux}$ decreased to 7%. *Figure 4.8* indicate that percentages of $UDI_{>2000Lux}$ to not be significant for building orientations from the north. For instance, 25% of the area in each building rotation has obtained high illuminance levels, when variation of the daylight device projection is 1.50 m. In light of this finding when device openings vary from 1.50 m to 2.00 m, $UDI_{>2000lux}$ percentage ranges achieved 25% to 0% for most building rotations. Also, in this case study 55-60% of a high illuminance level is obtained when daylight devices projection from 0.50 m to 0 m.

For the analysis of over illumination, a cut off line of 30% was set up. In this case, the devices that show that will not exceed daylight levels over 2000lux for 30% of the time are the devices with the openings 2m, 1.75m and 1.5m. The rest of the devices would provide increase levels of glare due to the increased time that lighting levels are over the 2000lux maximum target. Also, in this case study a further assessment was conducted using GP and DA_V to analyse daylight comfort in the space.

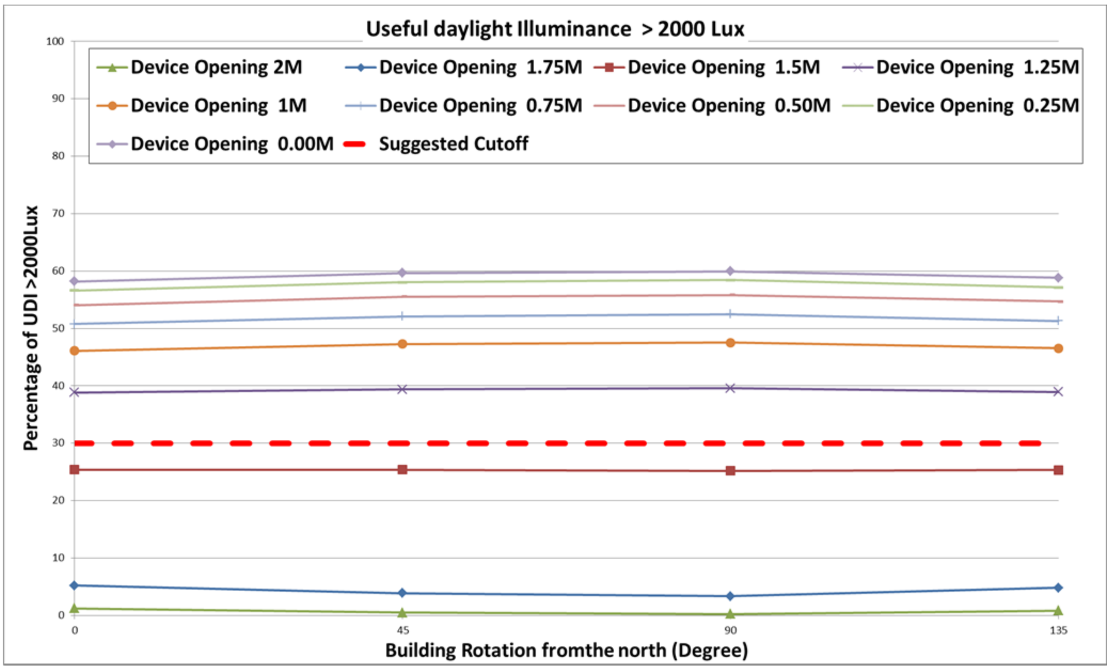


Figure 4.7. UDI exceeded ($UDI_{>2000Lux}$) regarding device projection.

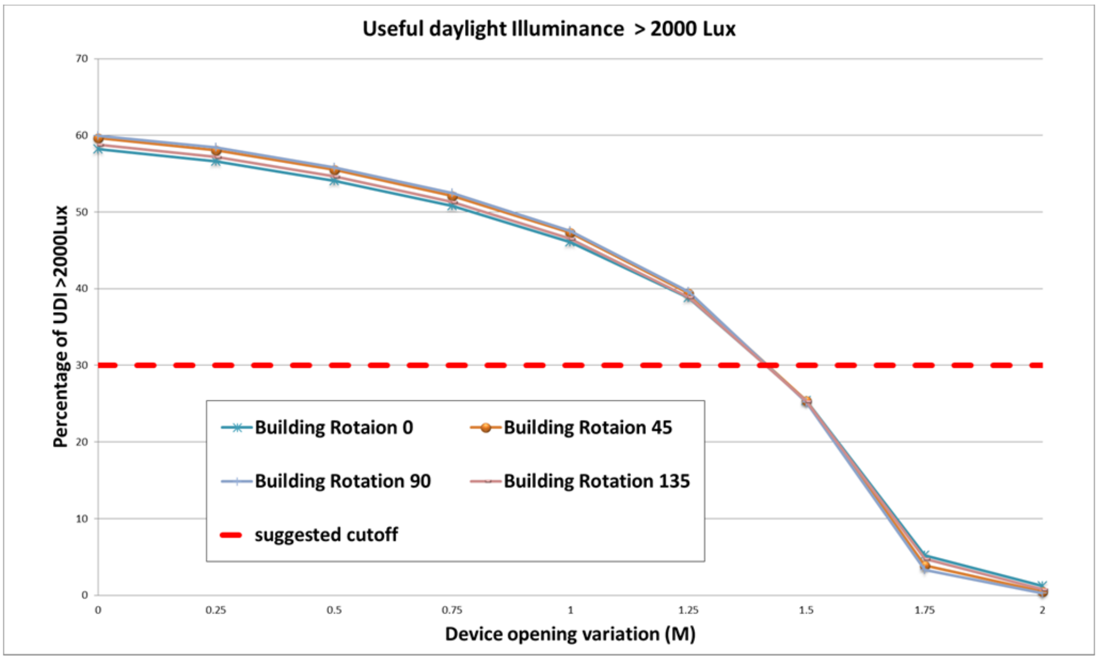


Figure 4.8. UDI exceeded (UDI$_{>2000Lux}$) regarding building rotation.

4.1.4 Daylight Glare Probability (GP) analysis

With respect to the daylight device projection for different building rotations, the prevalence of GP (i.e. > 2000 lux) is shown in *Figure 4.9*. In the DIVA plug-in, when sensors receive negative percentage values it indicates that the sensors have been exposed to > 2000 lux for some duration (from -10% to -100%). Therefore, to calculate the fraction of the floor area exposed to potential glare conditions in this case study, the number of sensors with negative percentages values has been counted. *Figure 4.9* shows only two daylight devices projection (2.00 m and 1.75 m) have been located under the suggested cut-off line. In this case study suggested cut-of line located on the 30%. The values for GP less than 30% are considered a good comfortable daylighting level in the building, this means that each sensor during the simulation received less than 30% of UDI >2000 lux and a GP value ≥2000lux is the target for appropriate performance. The minimum glare potential for 1.75 m and 2.00 m was obtained at 90^0 building rotation which is 19% and 0.2% respectively. However, when daylight device projections change from 0 m to 1.50 m, 49% to 78% of the sensors on the floor area present a glare probability. For all building rotations, glare potential decreases by increasing the device projection. *Figure 4.10* clearly shows two of the simulated shading designs with glare probabilities below the suggested cut-off of 30% of the occupied area, (1.75 m and 2.00 m projections) within each variation on projection, changing the building orientation does not significantly on the GP.

As it would be reasonable to expect, the optimal value with respect to glare potential for this system would be where the shading projection was maximal (2.00 m projection). In this case, the lowest GP was found at the orientation 90°. The high level of protection offered in this scenario may be associated with insufficient daylight generally, so it is observed that the less restrictive example where at 1.75 m is also to be considered as performing acceptably according to the target set for GP in this study.

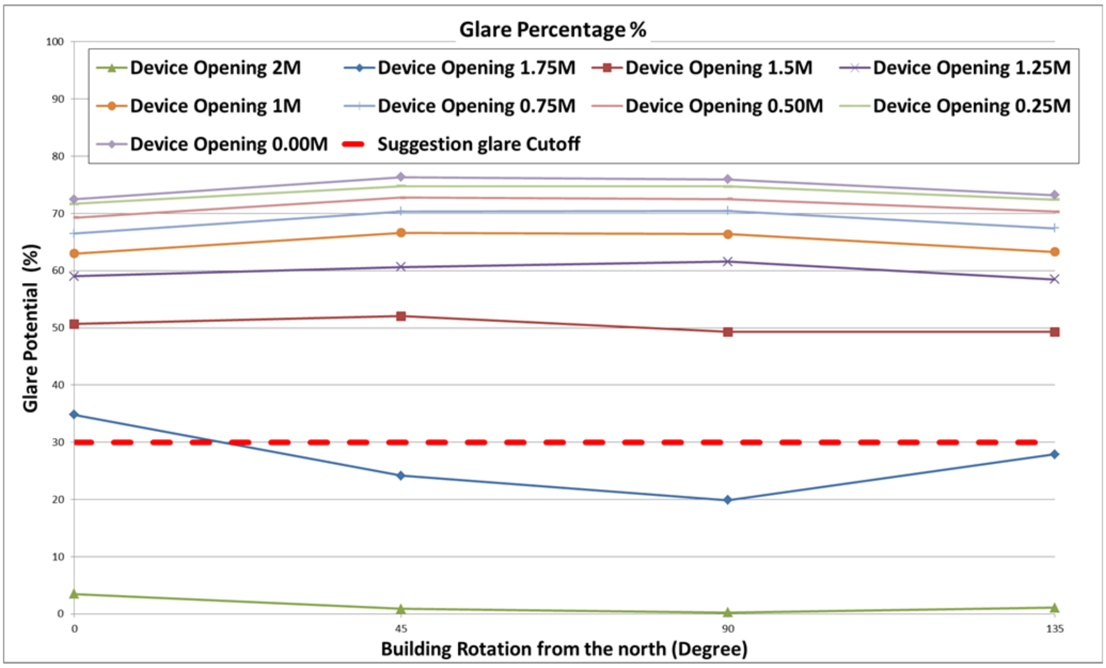


Figure 4.9. Percentage of Glare Probability regarding device projection.

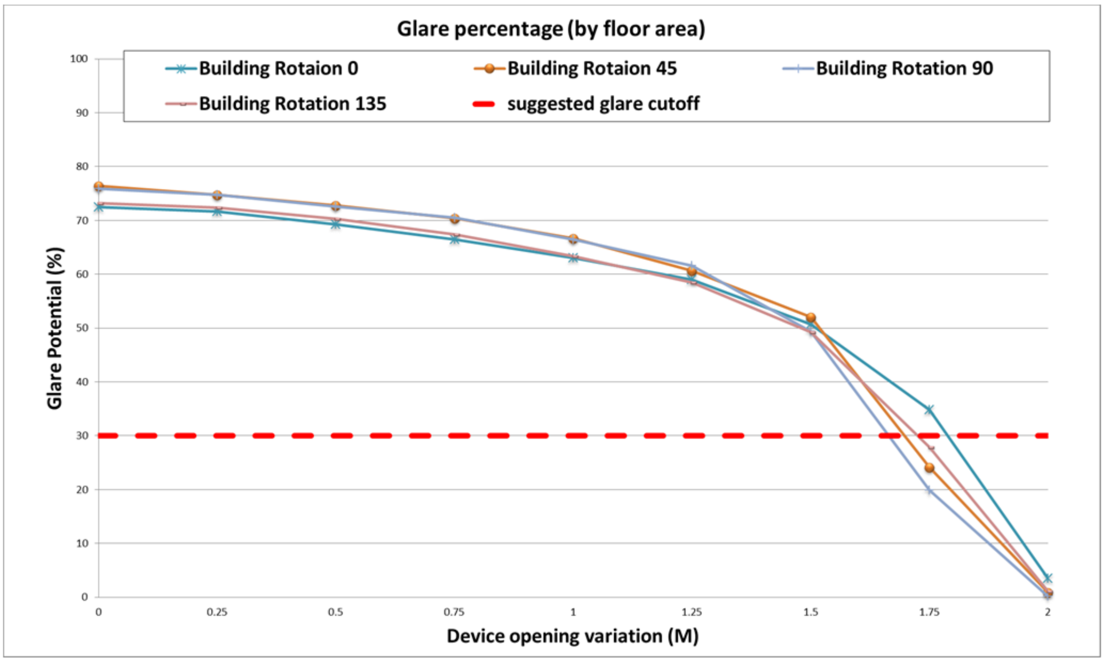


Figure 4.10. Percentage of Glare Probability regarding building rotation.

4.1.5 Daylight Availability (DA_V) Analysis

Daylight availability in the GH plug-in analysis of daylight performance meets the daylight comfort level in the interior space. Also DA_V is a combination method of $UDI_{100\text{-}2000lux}$ and Daylight Autonomy for daylight analysis. The effects of device opening and building rotation on $DA_{V200lux}$ have been examined in this section. As can be seen in *Figure 4.11*, $DA_{V200lux}$ percentage for two daylight device variations (1.75 m and 2.00 m) increases to more than 65%. On the other hand all other daylight device variations fall under the suggested cut-off (60%). However as indicated by the how frequently the illuminance values fall below 100 lux, more than 10% of the area are below acceptable daylight levels when the daylight device projection of 2.00 m is located on the façade system. Given these findings, it is considered that device projections of 1.75 m is the most appropriate to provide appropriate daylight comfort levels.

Consequently (*Figure 4.12*) $DA_{V200lux}$ result from daylight projection of 1.75 m is more meaningful; because annual percentages per sensors have increased from 65% to 80% by increasing the building rotation. For instance, for daylight projection of 1.75 m when the building location rotated 90^0 from the north $DA_{V200lux}$ increased more than 80% of the sensors on the floor area. Also $DA_{V200lux}$ percentages on other building rotations (0^0,45^0 and 135^0) achieved 65%, 75% and 72% of the area respectively.

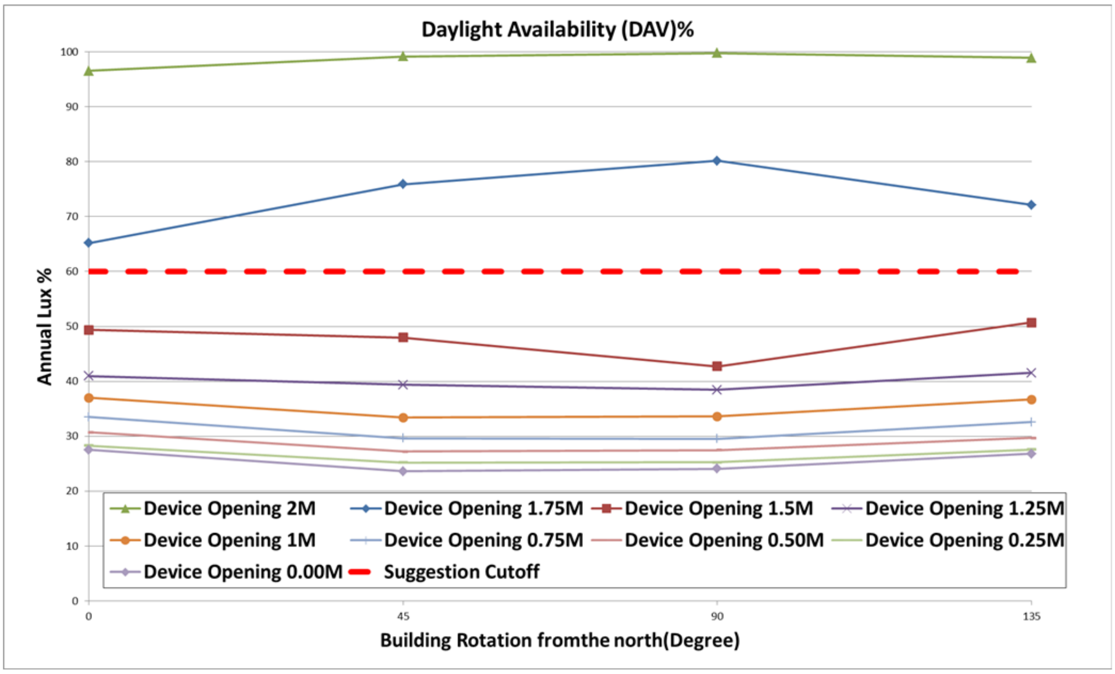


Figure 4.11. Daylight Availability regarding variation of daylight device projection.

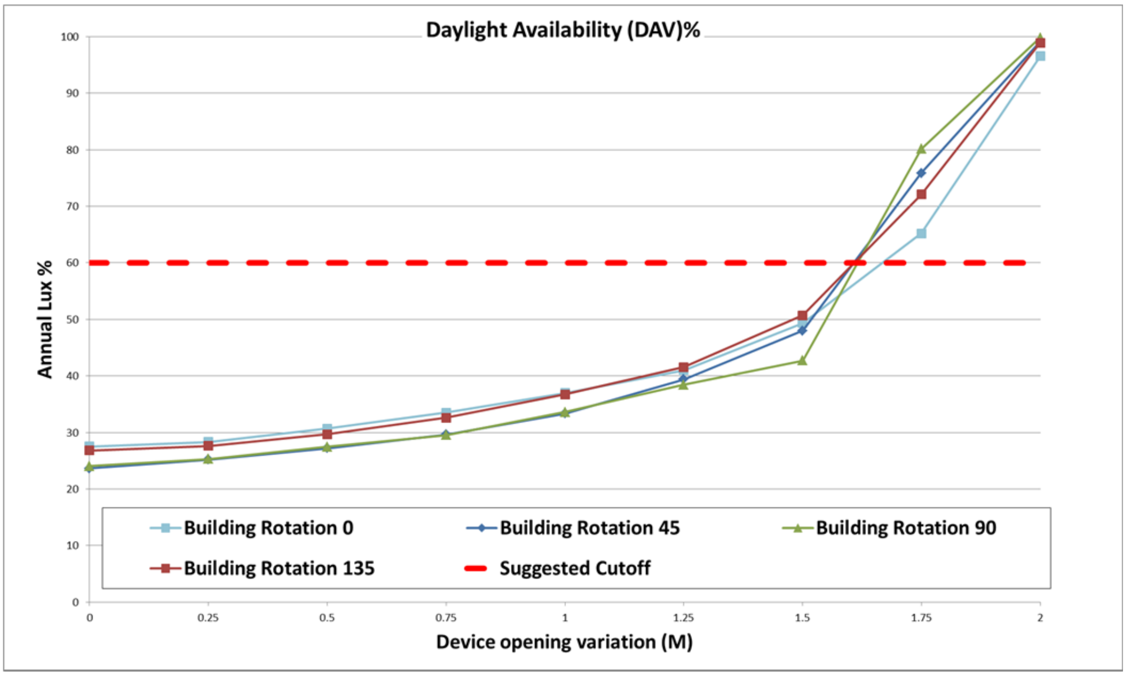


Figure 4.12. Daylight Availability regarding building rotation.

4.1.6 Esplanade building Results discussion

This section examines and compares the Climate based daylight metrics (CBDM) and graphical visualization of DAV200lux results to establish the optimum daylight device projection and building position. CBDM provided more information to analyse the building environment and optimize energy such as daylight quality (Garcia-Hansen 2012). According to the daylight analysis in this case, the useful daylight level was achieved for more than 70% of the area when the daylight device projection are1.50 m, 1.75 m and 2.00 m for most building rotations. As it was made clear in the glare probability analysis, the glare potential approaches zero at a device projection of 2.00 m for all building rotations. Therefore, a device projection of 2.00 m is suitable for daylight comfort in the case study buildings. In other words, at this point UDI fell short (<100lux) increase due to the closed geometry (2.00 m). For this reason, the optimum value of glare potential is obtained at a daylight device projection of 1.75 m for the building rotation of 90^0 from the north. Also, $DA_{V200lux}$ results from daylight device projection of 1.75 m are more meaningful, because annual percentages per sensors increased from 65% to 80% by increasing the building rotation (*Figure 4.13*). The $DA_{V200lux}$ annual hourly occupancy schedule was calculated from 8am to 6pm weekly and 200 lux was selected as the target minimum illuminance (2000lux is the upper threshold). Results from *Figure 4.11* above show $DA_{V200lux}$ for iterations with a device projection of 1.75 m as the highest. In DA_V metric from GH plug-in the over light (such as GP) a negative appears in from of the DAV percentage. This symbol appears when the sensor considered values are 10 times higher than the target illuminance and in this case 2000lux is present in that sensor for at least 5% of the time. The results show that the projection 1.75 m has no problems with over light and glare. Despite this finding, just one daylight device projection (1.75 m) among the daylight devices and 90^0 building rotation can provide daylight comfort levels in the Esplanade building.

In final consideration, regarding to CBDM results in this case study author explains some points:

- Building orientation from the north (0^0 to 135^0) is not significant on results, because in this case study the façade is symmetric in terms of device opening projections. So, building orientation of 45^0 from the north is enough for the simulation, but author examined other orientations to more understanding what's happened during the simulations.
- Values for $UDI_{100\text{-}2000Lux}$ and $DA_{V200Lux}$ higher than 60% are considered a good comfortable daylighting level in the building, and a GP value less

than 30% is the target for daylight appropriate performance. This means that, when the device projection in UDI and DA_V simulations located on the cut-off line sensors receive more than 60% values indicates that the sensors have been exposed to comfortable daylight levels regrading to $UDI_{100\ to\ 2000Lux}$ and $DA_{V200Lux}$. In contrast when GP value is located under the cut-off line, less than 30% of sensors (the floor area) it means that the rest of the sensors are exposed to good comfortable daylight level without potential glare conditions most of the time. Also, the optimum level of protection offered in all CBDM graphs and graphical visualization may be associated with insufficient daylight generally, so it is observed that the less restrictive examples where at 2.00 and 1.75 m are also to be considered as performing acceptably according to the target set for GP in this study.

- The sun paths are different due to factors such as the location, setting position and duration of the day and night. Therefore, during the summer months in south eastern Asia (like Singapore), the sun will be traveling at the highest path across the sky. In the morning the sun will rise due south of east, then crosses the meridian due south at noon and seething a little due south of west. The duration of the day is longer relative to the night as the sun across the sky. Regarding to sun path analysis in Singapore, more than six months of the year length of the day is longer than 12 hours and the sun covered façade system on Esplanade building. In final consideration of CBDM and sun path analysis, the result indicates that there was very little difference in vary of the daylight device projections. Its means that the parameter really did not make a difference results and are not significant.

4.1.7 Future Daylight Analysis

A graphical visualization of the $DA_{V200lux}$ and climate based results, still do not show much variation with building orientation. The reason could be how the annual analysis is presented. While an iteration of rotation 90 degree for all different projection show glare in the east and west, these would happen at different times of the day. This solution means that the morning will have higher levels in the east (and probably glare), and low in the west, and vice versa in the afternoon, but is not shown as an annual average. As a result, the next step in this research will be to the distribution of horizontal illuminance levels using point in time simulation, for equinox and solstices, at three times of the day (9am, 12pm, and 3pm).The purpose would be to assess performance throughout the day and at different seasons.

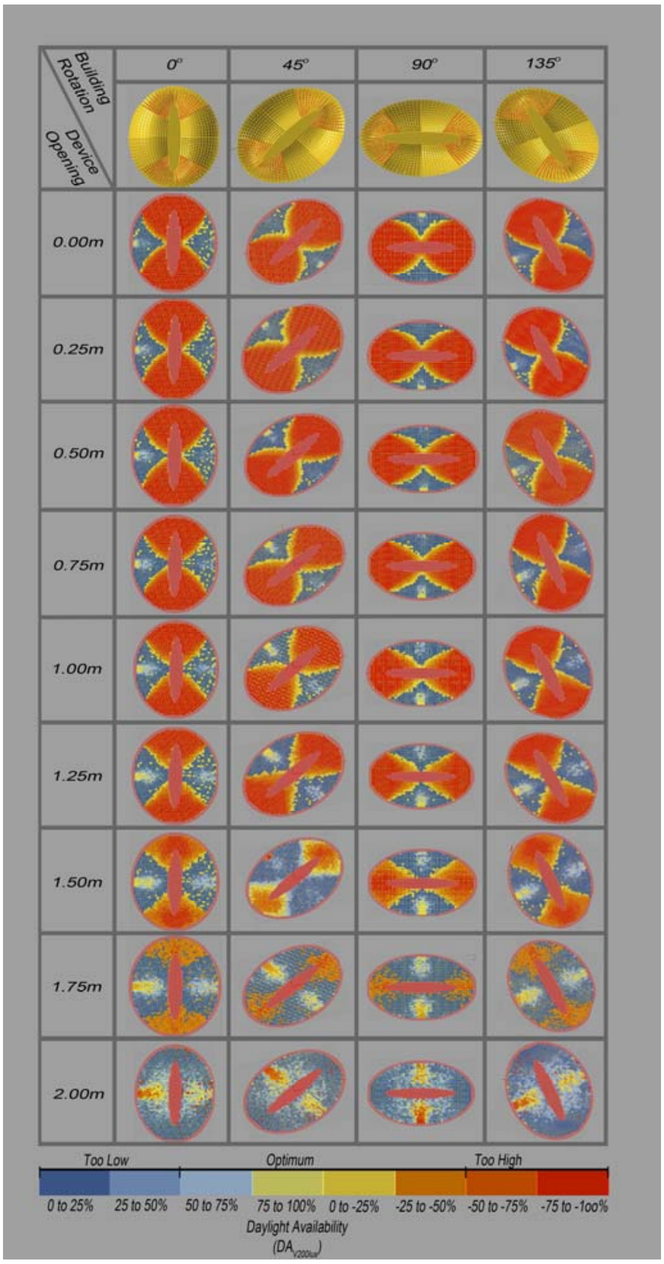


Figure 4.13. Graphical visualization of the GH/DIVA plug-in results regarding daylight device projection and building rotations.

4.2 KUNSTHAUS GRAZE DAYLIGHT ANALYSIS AND OPTIMIZATION

For the design optimization process of the design based on the Kunsthaus Gtaze daylight performance with the $DA_{V200lux}$, UDI $_{100\text{-}2000lux}$, and glare probability is used. This section presents the assessment of two approaches to find the optimum daylight performance for this design. The approaches are:

- Variation of the projection of nozzle on façade system, to find the optimal dimension
- Variation of nozzle orientations from the north, to find optimum orientation

Nozzles in this research have been redesigned to obtain the device positions on the cladding system. These nozzles as daylight devices in case study one have been controlled by sliders in the GH plug-in to find the optimal dimension. Also, Nozzle apertures have been changed in three steps from 0.50m to 1.00 m to find the optimum natural light inside the building. For this case study, and based on the real building, the height of the nozzles on the façade has been fixed at 2.50 m and the radius of lower aperture nozzles have been fixed at 1.00 m. However, radiuses of upper aperture from the nozzles have been changed from closed (0.50 m) to maximum opening (1.00 m), as in *Figure 4.14*.

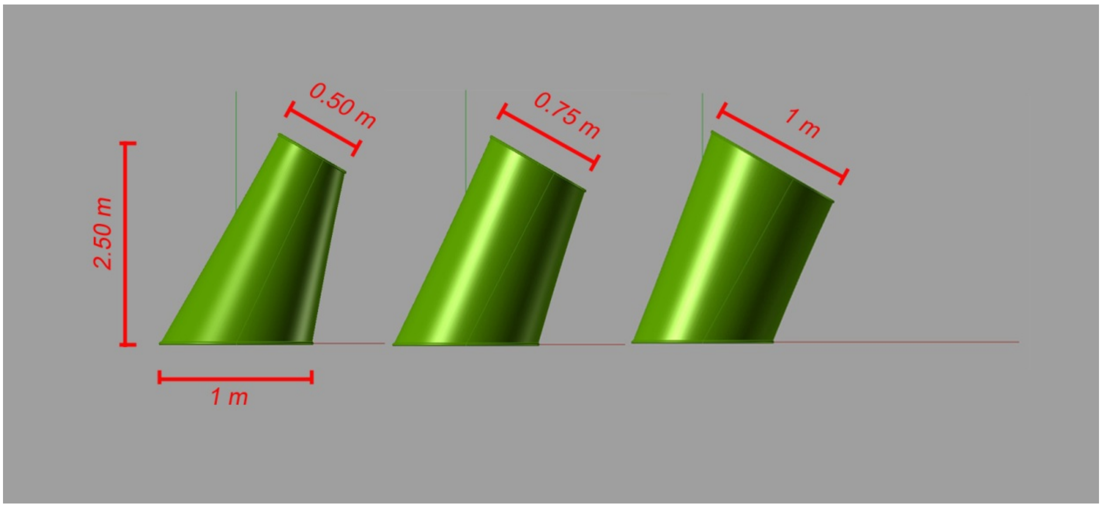


Figure 4.14. Vary nozzle aperture on the Kunsthaus Graze façade system.

Nozzle rotation from the north is another way to maximize daylight comfort in the space. Daylight device orientation is an important method for designers and engineers to find the optimum position of the devices on the façade system regarding the sun path. Therefore, nozzles are rotated four times (north, east, south and west) to assess the effect of device orientation on daylight performance (*Figure 4.15*). These two processes were conducted in parallel to achieve visual comfort and optimum daylight performance in the interior space. In this case study such as Esplanade building simulation specific material surface reflectivity is assigned to the various elements of façade system (*Table 4.1*).

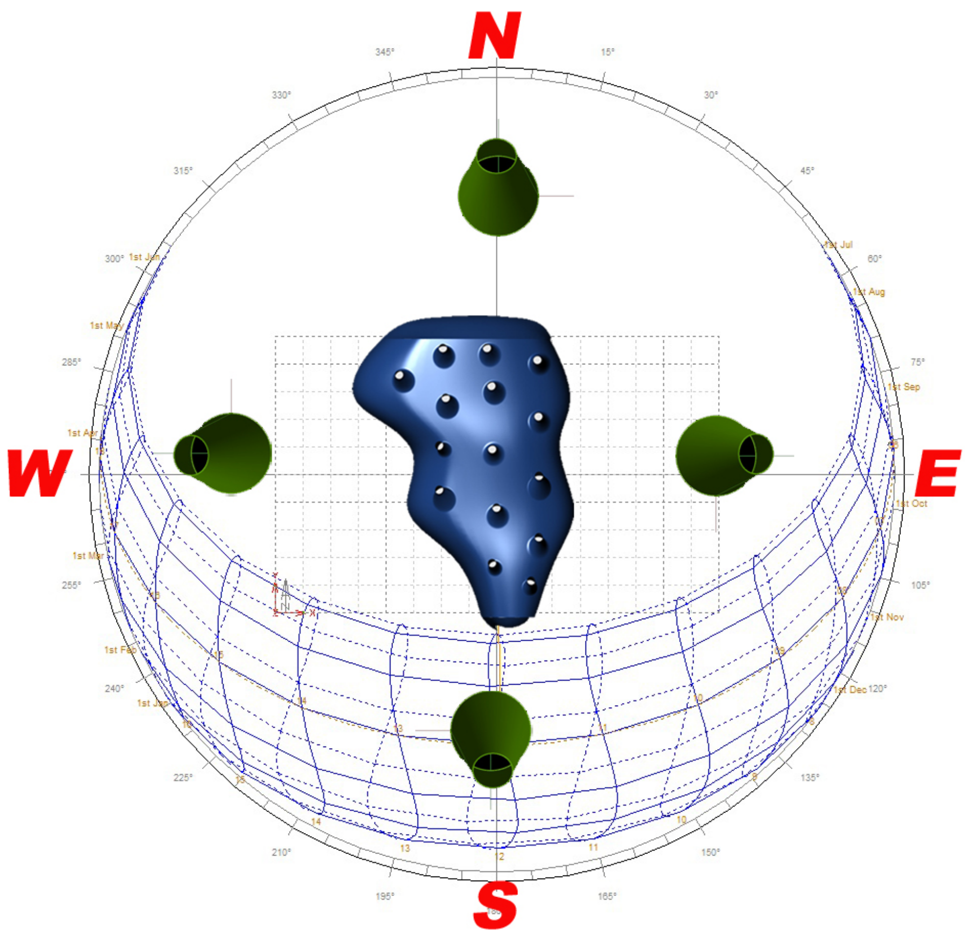


Figure 4.15. Variation of nozzle orientations from the north

4.2.1 Useful Daylight Illuminance 100-2000lux ($UDI_{100\text{-}2000lux}$)

The horizontal axis in *Figure 4.16* shows the variation of nozzle upper apertures from 0.50 m to 1.00 m and the vertical axis shows the percentage of annual illuminance when the daylight level is between the 100 to 2000 Lux ranges. This figure also illustrates direction of nozzle rotation from the north with the colour lines. That is, a maximum of $UDI_{100\text{-}2000lux}$, about 55- 60%, was obtained for a nozzle aperture of 0.75 m and 1.00 m was achieved for the east rotation. The annual percentage of the useful daylight (100 to 2000 lux) per sensor (839 sensors are placed on the measuring grid at 0.85 m above the ground floor) is calculated using a weekly 8am to 6pm occupancy file.

Moreover, the lower percentage of $UDI_{100\text{-}2000lux}$ (achieved) of 10-40% was obtained for the 0.50 m nozzle aperture with most device positions (north, east, south and west). For instance, when the nozzle projection is 0.50 m, the annual illuminance level of nozzle rotations from the north achieved 32%, 40%, 30% and 13% $UDI_{100\text{-}2000lux}$ respectively. However *Figure 4.17* highlights that the variation of upper aperture is 0.50 m, 13-40% $UDI_{100\text{-}2000lux}$ is achieved for most nozzle rotations. In contrast, when the upper aperture is 1.00 m, UDI percentage ranges are 48-60% due to the space being over light. These results show how the lower percentage $UDI_{100\text{-}2000lux}$ ranges are obtained for the west nozzle rotation and higher percentage achieved from the east rotations. Therefore the $UDI_{100\text{-}2000lux}$ percentage from the north rotation is considered a good comfortable daylight level. Also the annual occurrence of useful daylight levels in the building a further assessment was conducted using DAV_{200lux} to analyse daylight comfort in the space.

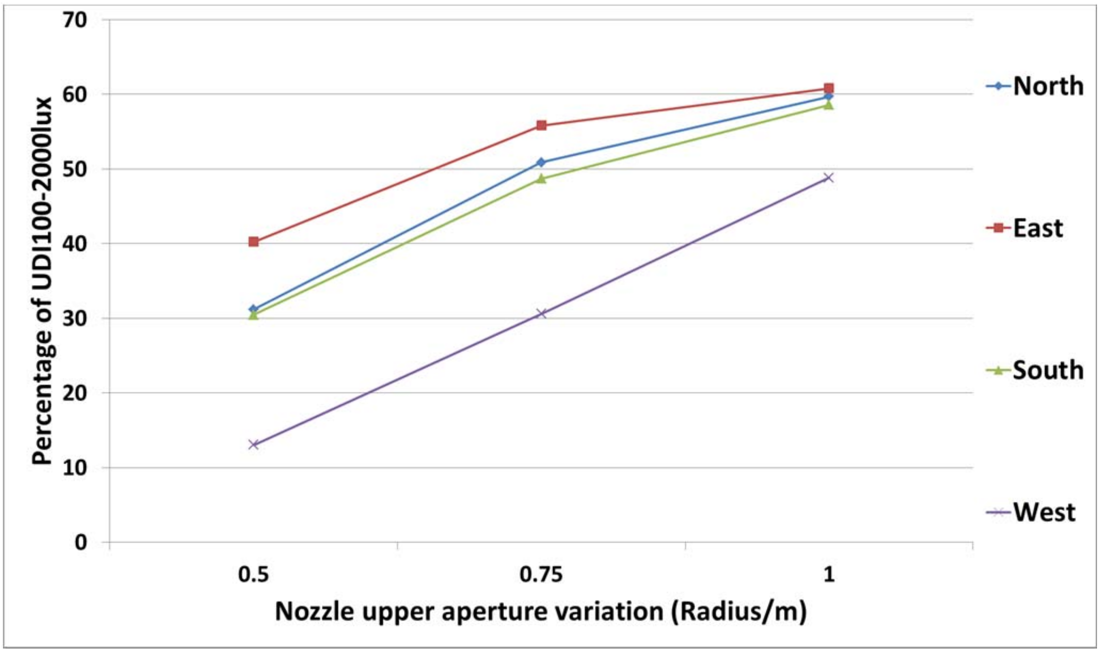


Figure 4.16. $UDI_{100\text{-}2000lux}$ regarding the nozzle rotations from the north.

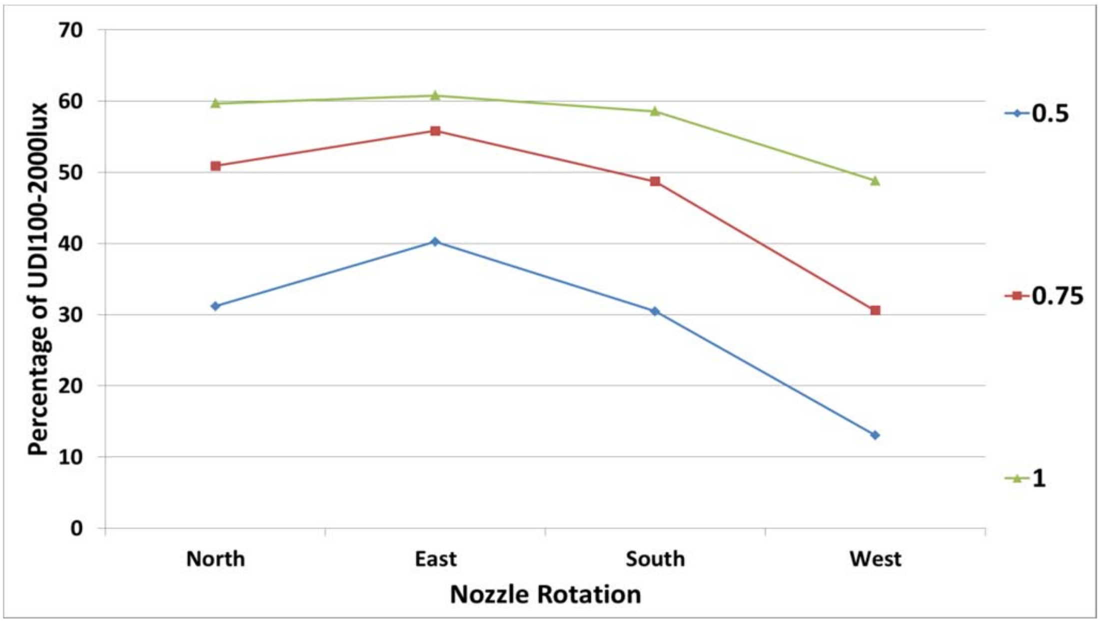


Figure 4.17. $UDI_{100\text{-}2000lux}$ regarding nozzle upper aperture.

4.2.2 Useful Daylight Illuminance fell short ($UDI_{<100lux}$)

Figure 4.18 illustrates the percentage of low annual illuminance level (less than 100 lux) in the building when the upper apertures and nozzle orientations have been changed. When looking at UDI fell short a good solution would need to demonstrate low percentage of UDI fell short. The results indicate for example that when the nozzle is rotated to the east, UDI percentage ranges achieved low illuminance levels from 37-58% for most upper aperture. For example, 38%, 43% and 58% $UDI_{<100lux}$ have been achieved for nozzle projection of 1.00 m, 0.75 m and 0.50 m respectively. In contrast, when nozzle positions rotated to the west, $UDI_{<100lux}$ percentage obtained 52- 87% for all upper apertures. An example of this result is that 86% of the area attained a low illuminance level, when the upper aperture was 0.50 m and 52% of the area obtained UDI fell short when the upper aperture was 1.00 m. However, 58% and 38% $UDI_{<100lux}$ was obtained when the nozzle positions were located to the east and the upper apertures were 0.50 m and 1.00 m. On the other hand, when the upper aperture is reduced from 1.00 m to 0.50 m, the UDI fell short increased from 20% to 40% of the sensors from most nozzle rotations. For instance, in the north and south rotations, the $UDI_{<100lux}$ percentage range increased from 40% to 68%, when the upper apertures closed from 1.00 m to 0.50 m.

Figure 4.19 presents the percentage of low illuminance level ranged from 43% to 68% when the nozzle projection is 0.75 m. For instance, $UDI_{<100lux}$ percentage ranges obtained 48%, 43%, 51% and 68% for nozzle rotations from the north to the west respectively. Consequently, lower percentages of UDI fell short are achieved for bigger apertures, but also the orientation has an effect, with north and east orientations showing more optimal results (lower UDI fell short). However, in the next stage of analysis more detail assessment of these solutions is undertaken to evaluate glare probability using UDI exceeded and DAv, specially for the best performing solutions under UDI fell short.

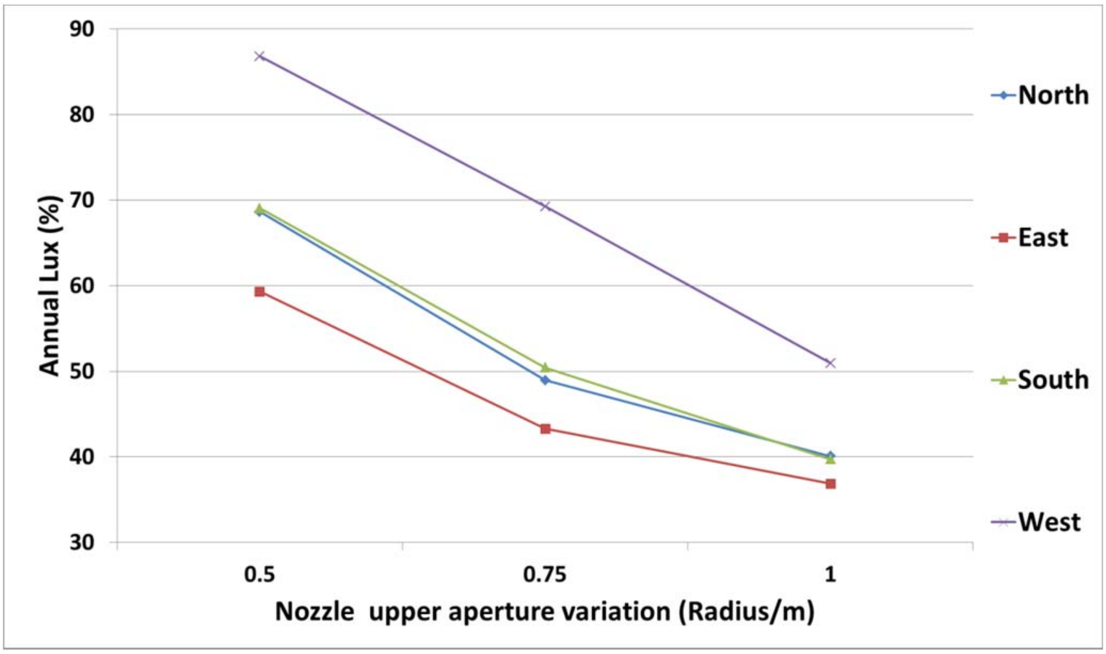


Figure 4.18. UDI fell short regarding nozzle rotations from the north.

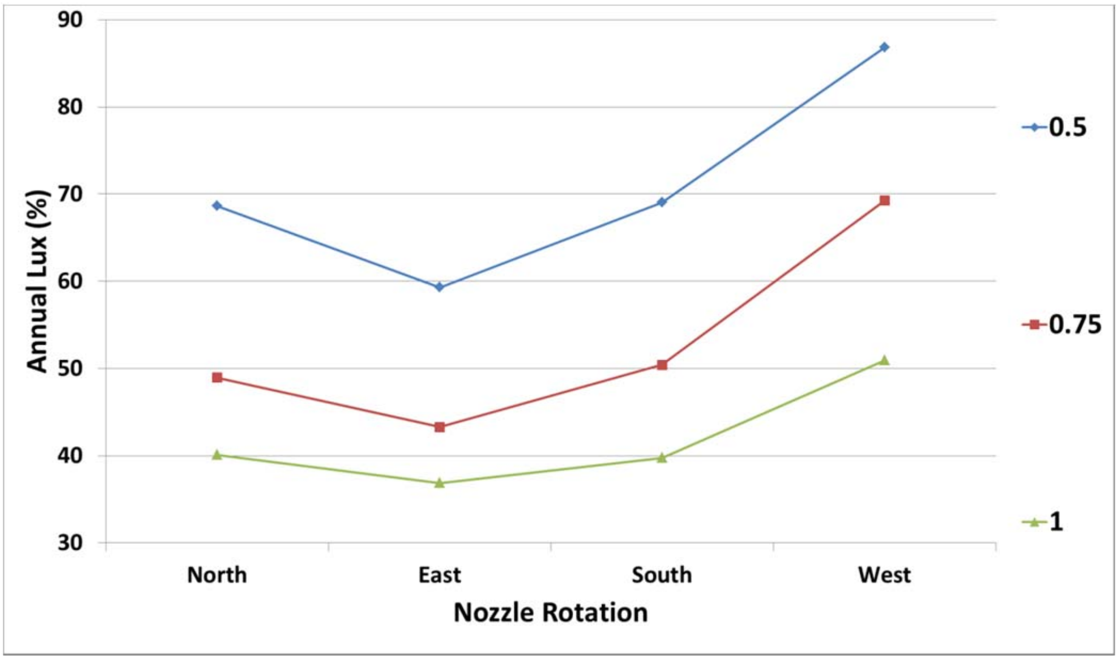


Figure 4.19. $UDI_{<100lux}$ regarding nozzle projection.

4.2.3 Useful Daylight Illuminance exceeded ($UDI_{>2000lux}$)

Following this analysis and the nozzle rotations changed from the north to the west, two upper apertures of 0.75 m and 1.00 m obtained more than 0.75% high illuminance level on the sensors (*Figure 4.20*). That is, 2.3 % $UDI_{>2000lux}$ was achieved when the upper aperture was 1.00 m and nozzles rotated to the east. Unlike the previous example in the same nozzle rotation, less than 0.5 percentage of $UDI_{>2000lux}$ was obtained on the floor area when the nozzle aperture was 0.50 m. In can be seen in this figure the minimum high annual illuminance level is achieved for nozzle rotations to the north and west. *Figure 4.21* clearly indicates that only one upper aperture variation (1.00 m) attained more than 1.5 % $UDI_{>2000lux}$, when the nozzles rotated to the east and south. Therefore the percentage of $UDI_{>2000Lux}$ is not significant due to the north and the west rotations and closed nozzle apertures (0.75m and 0.5m).

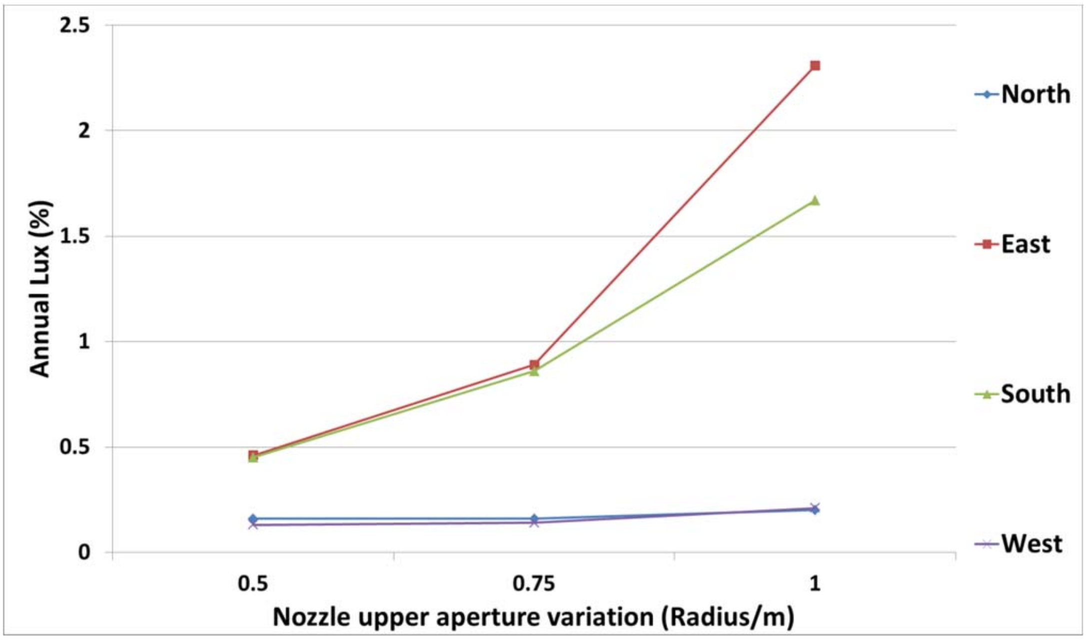


Figure 4.20. UDI$_{>2000lux}$ regarding the nozzle rotations from the north.

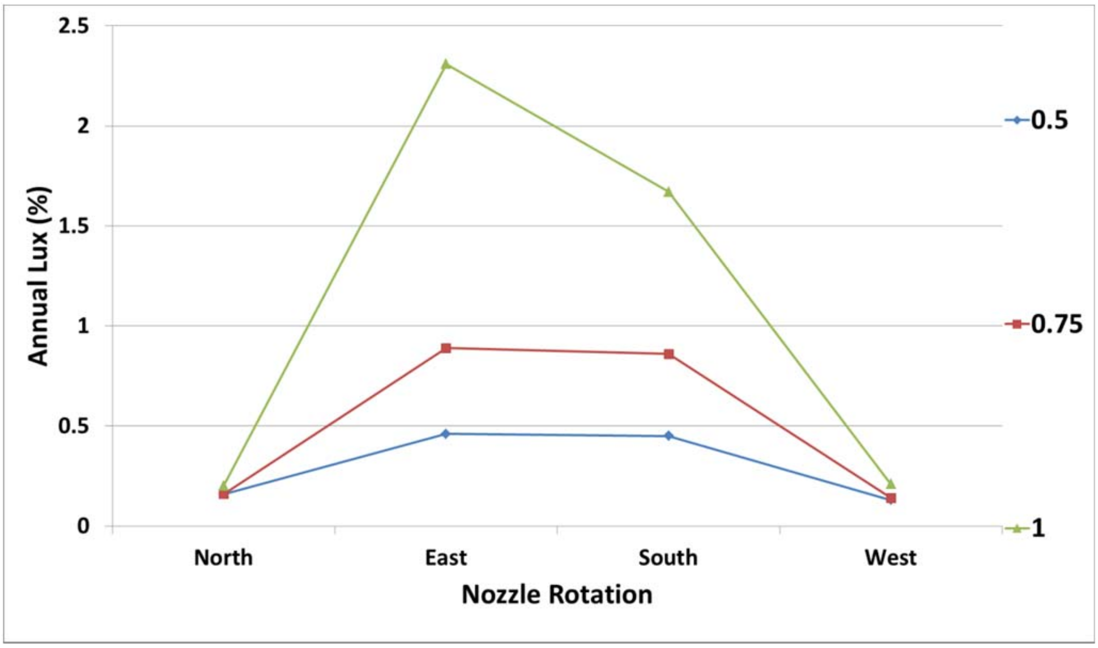


Figure 4.21. UDI$_{>2000lux}$ regarding nozzle projection.

4.2.4 Percentage of Glare Probability (GP) analysis

With respect to the daylight device projection for different building rotations, the prevalence of GP (i.e. > 2000 lux) is shown in *Figure 4.22*. In the DIVA plug-in, same as first case study when sensors receive negative percentage values it indicates that the sensors have been exposed to > 2000 lux for some duration (from -10% to -100%). Therefore, to calculate the fraction of the floor area exposed to potential glare conditions in this case study, the number of sensors with negative percentages values has been counted. Following the glare analysis for two nozzle rotations (the east and the south), and nozzle projection from 0.75 m to 1.00 m the over light per sensors increased from 0.2% to 22%. This figure clearly indicates that the highlight percentage was achieved for less than 0.2% of the sensors, when the nozzle rotations located to the north and the west. The minimum glare potential for 0.50 m, 0.75 m and 1.00 m was obtained at the north and west nozzle rotation which is approaching to zero.

The maximum glare potential for open aperture 1.00 m was obtained at the east and the south nozzle rotations, 22% and 13% respectively (*Figure 4.23*). As it would be reasonable to expect, the optimal value with respect to glare potential for this system would be where the nozzle projection is maximal (1.00 m projection). In this case, the lowest GP was found at the north and west. The high level of protection offered in this scenario may be associated with insufficient daylight generally, so it is observed that the less restrictive examples where at 0.75 m is also to be considered as performing acceptably according to the target set for GP in this study. Therefore, percentage glare probability was identified as not significant when the upper apertures were closed from 0.75 m to 0.50 m. For all nozzle rotations the glare potential decreases by closing the upper apertures.

As it would be reasonable to expect, the optimal value with respect to glare potential for this system would be where the nozzle projection was maximal (1.00 m projection). In this case, the lowest GP was found at the nozzle orientation from the north and west. The high level of protection offered in this scenario may be associated with insufficient daylight generally, so it is observed that the less restrictive examples where at 0.50 and 0.75 m are also to be considered as performing acceptably according to the target set for GP in this study.

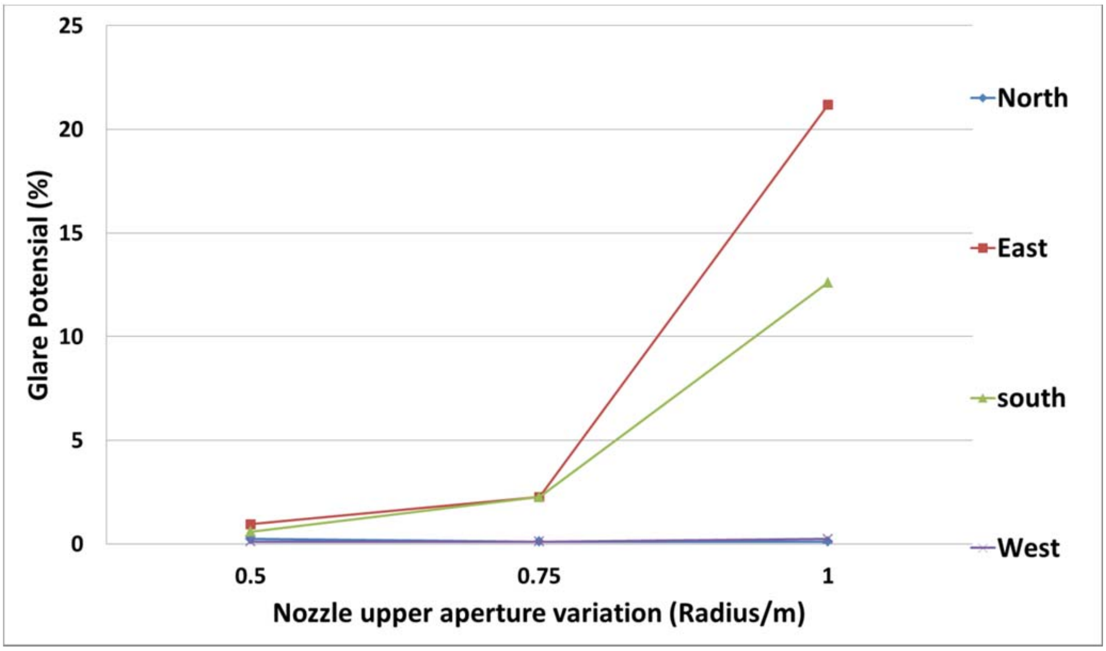


Figure 4.22. Glare Probability regarding nozzle rotations from the north.

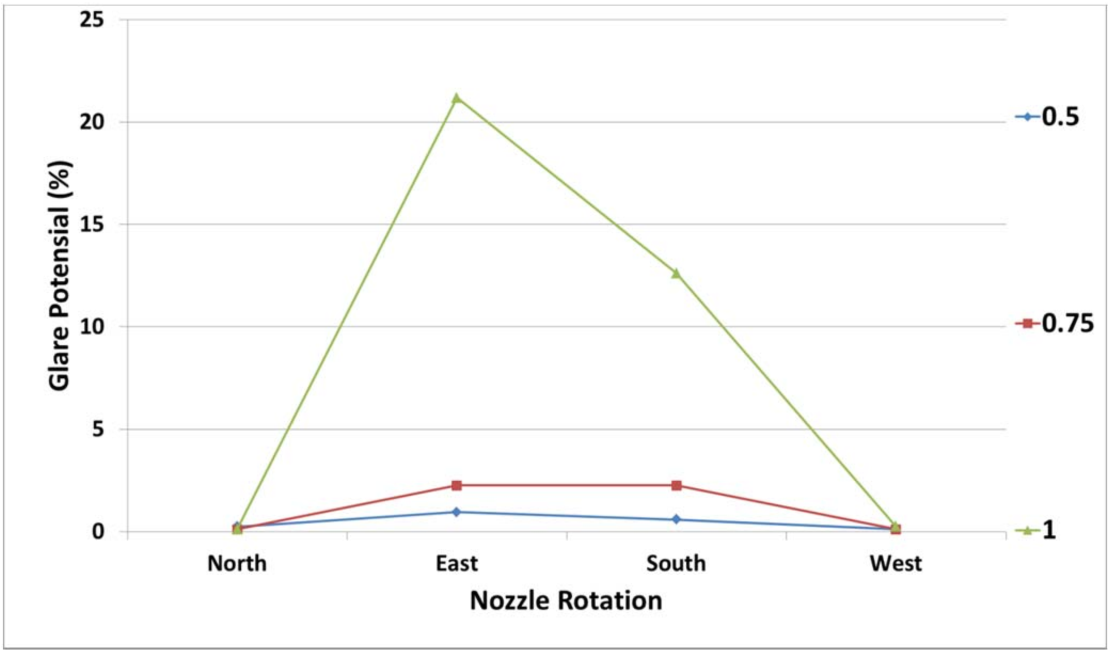


Figure 4.23. Glare Probability regarding nozzle projection.

4.2.5 Daylight Availability-200lux ($DA_{V200lux}$)

The effects of device projection and nozzle rotation on $DA_{V200lux}$ have been examined in this section using Daylight availability. As can be seen in *Figure 4.24*, $DA_{V200lux}$ percentage for all nozzle projection (0.50 m, 0.75 m and 1.00 m) increases to more than 96%. However as indicated by the how frequently the illuminance values fall below 100 lux, more than 12% of the area are below acceptable daylight levels when the nozzle projections of 0.50 m and 0.75 m are located on the façade system. On the other hand 86% of the area achieved 200 to 2000lux daylight levels, when a 1.00 m upper aperture is located on the façade system and nozzles rotated to the south. Regarding glare probability and $DA_{V200lux}$ analysis, direct sun light coming inside the building from the south, when a 1.00 m upper aperture is located on the façade and the daylight levels are outside the $DA_{V200lux}$ percentage. Therefore, nozzle aperture 1.00 m is not suitable for daylight comfort in this case study.

Given these findings, it is considered that device projections of 0.50 m and 0.75 m are the most appropriate to provide appropriate daylight comfort levels. On the other hand the $DA_{V200lux}$ percentage on the upper aperture of 0.50 m is not suitable for daylight comfort in the building, because more than 60% of the area achieved UDI fell short (regarding UDI analysis). Despite this finding, just one projection (0.75 m) of the nozzle can provide daylight comfort levels.

Consequently a DAV_{200lux} result from daylight projection of 0.75 m is more meaningful; because annual percentages per sensors have increased more than 97% by nozzle rotation from the north and west (*Figure 4.25*). For instance, daylight projection of 0.75 m, when the device rotated to the north and west $DA_{V200lux}$ increased more than 99% of the sensors on the floor area.

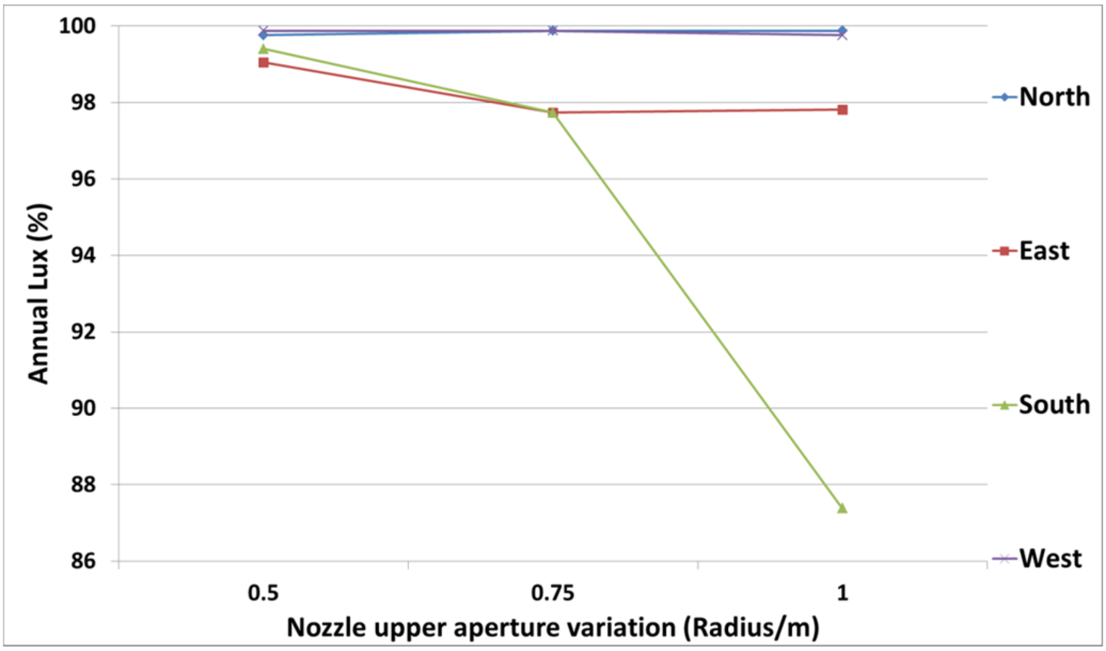


Figure 4.24. $DA_{V200lux}$ regarding nozzle rotations from the north

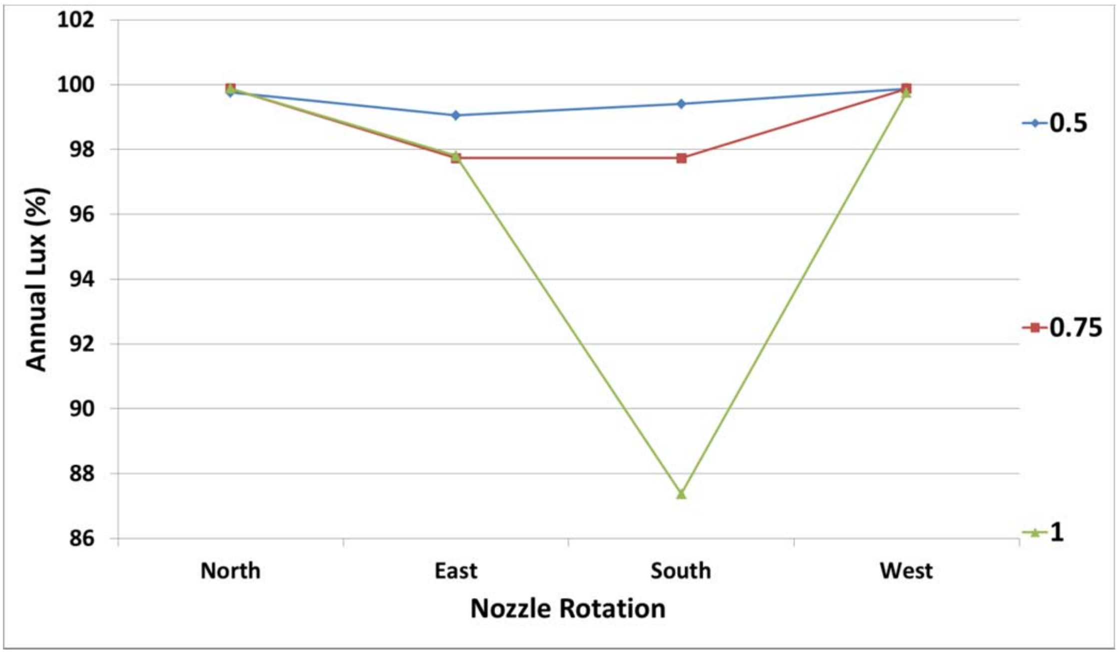


Figure 4.25. $DA_{V200lux}$ regarding nozzle projection.

4.2.6 Kunsthaus Graze Results discussion

The daylight simulation and analysis in this case shows that the useful daylight level achieved more than 55-60% of the area when nozzle upper apertures are 0.75 m and 1.00 m for the east rotation. As it was made clear in the glare probability analysis, the glare potential approaches zero at a nozzle projection of 0.50 m and 0.75 m for the north and west nozzle rotations. Therefore, a nozzle opening of 0.50 m is not suitable for daylight comfort in the Kunsthaus Graze building. That is, $UDI_{<100lux}$ increases at this point due to the closed geometry which means the optimum value of glare potential, regarding the comfort level will be obtained at a nozzle opening of 0.50 m for the nozzle rotation from the west. Also, regarding to glare probability and $DA_{V200lux}$ analysis, direct sun light coming inside the building from the south, when a 1.00 m upper aperture is located on the façade and the daylight levels are outside the $DA_{V200lux}$ percentage. For this reason, the optimum value of glare potential regarding comfort is obtained at a nozzle projection of 0.75 m for the nozzle rotation of the north and west. Also, $DA_{V200lux}$ from the upper aperture 0.75 m is meaningful; because the annual percentages per sensors increased from 44% to 69% by nozzle rotations from the north. In $DA_{V200lux}$ the annual hourly occupancy schedule was calculated from 8am to 6pm weekly and 200 lux is selected as target minimum illuminance (2000lux is the upper threshold). In DAV metric from GH plug-in the over light (such as GP) a negative appears in from of the DAV percentage. This symbol appears when the sensor considered values are 10 times higher than the target illuminance and in this case 2000lux is present in that sensor for at least 5% of the time. Results from *Figure 4.25* above show $DA_{V200lux}$ for nozzle projection of 0.75 m achieved more than 97% for most nozzle rotations and highlighting that the projection 0.75 m has no problems with over light and glare. Despite this finding and regarding to graphical visualization of GH/DIVA plug-in results (on *Figure 4.26* these results are highlighted in reed) the aperture 0.75 m among the nozzles projection and the north and west rotation can provide daylight comfort levels in the Kunsthaus Graze building.

Consequently, results from CBDM simulations revealed several points in this case study:

- Nozzle rotation from the north to west is significant, because in this case study and based on real building Kunsthaus Graze nozzles located on the façade system to transfer natural light. Regarding to azimuth and elevation angle of the sun path in Austria, sunrise in summer months is at azimuth 60^0 (i.e. NE) and sunset at NW for winter solstice and at 120^0 (i.e.SE) and at 240^0 (i.e. SW), respectively, for summer solstice. Therefore, during the summer months in Austria, the sun will be traveling at the high path across the sky. In the morning the sun will rise due north of east, then crosses the meridian due south at noon and seething due north of west. The duration of the day is shorter relative to the night as the sun across the sky. Regarding to sun path analysis in Austria, more than six months of the year length of the day is less than 10 hours and the sun cannot cover façade system on the building. Also, during the winter months the sun will be traveling at the low path across the sky (10^0) and in the morning the sun will rise at 7:42 am due south of east, then crosses the seething due south of west at 4:30 pm. In final consideration of CBDM and sun path analysis, the result indicates that the equinox days and length of the daylight period was difference in this case study.
- Values for $UDI_{100\text{-}2000Lux}$ and $DA_{V200Lux}$ are considered a good comfortable daylighting level by nozzle rotation from the north and west in the building, and over light area percentage considered by nozzle rotation from the east and south. The optimum level of protection offered in all

CBDM graphs and graphical visualization may be associated with insufficient daylight generally, so it is observed that the less restrictive examples where at 0.75 m is also to be considered as performing acceptably according to the target set for GP and DA_V in this study (on *Figure 4.26* these results are highlighted in reed).

4.2.7 Future Daylight Analysis

The next step (not done for this thesis) would be to simulate the internal horizontal illuminance through point in time calculations for different times during the day and year to more clearly assess the nozzle projection and orientation effect. The aim would be to produce an optimization methodology for daylighting devices integrated with complex facades system.

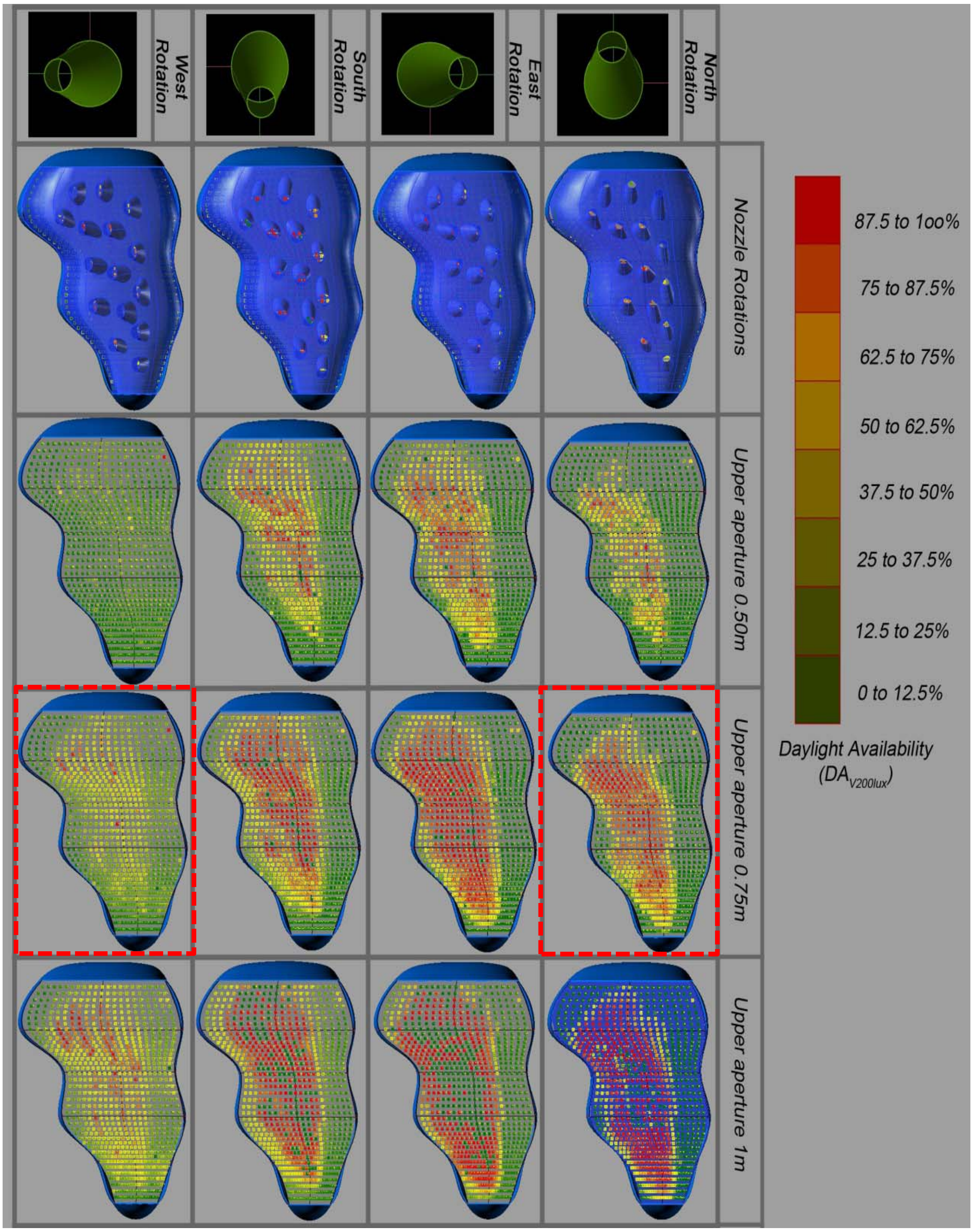


Figure 4.26. Graphical visualization of GH/DIVA plug-in results regarding nozzle projection and building rotations (Best solutions highlighted in red).

Chapter 5: Discussion and Conclusions

The purpose of this research was to investigate daylight performance of dayligthing devices integrated to the facades of buildings with complex geometries. Two case studies, buildings with climate responsive envelopes, were assessed. The building geometries were based on the Esplanade in Singapore and Kunsthaus Graze in Austria. Daylighting devices are currently not well incorporated within parametric façade system design processes, making the architectural and engineering integration of daylight devices in envelopes, with complex geometries a challenge, not only in terms of their design but also in terms of their performance evaluation. Parametric modelling allows the generation of new forms (complex geometry) in architecture but also enable to automatically generate a large range of alternative design solutions supporting geometric design explorations. Parametric modeling was used in this study to produce different iterations in the design parameters such as building and component orientation, daylight device projection, and tested there using daylight simulation in a comprehensive range of scenarios. Parameters such as dimension, inclination of the device, projected shadows and shape have been changed in order to maximize Daylight Availability and Useful Daylight Illuminance while minimizing glare probability.

The method for analysis of daylighting in building designs use was Climate-Based Daylight Modelling. This metric estimate of luminous quantities using realistic sun and sky conditions derived from standardized meteorological data. CBDM such as Useful Daylight Illuminance (UDI) and Daylight Availability (DA_V) are used to assess illuminance levels and glare probability (GP). The following steps are proposed for the assessment of daylighting performance of case study buildings with complex geometry:

- The case study buildings are modelled by parametric modelling plug-in called “Grasshopper” (GH).
- Through experimentation and evaluation daylight performance is assessed (DIVA).

GH plug-in is a suitable environment for architects and engineers to generate three dimensional models in a flexible way, to control the design process. The DIVA plug-in, designed for Rhinoceros, evaluates the daylighting performance at each point of the design space. Within DIVA plug-in the annual percentage of the daylight metric per sensor is calculated using a weekly 8am to 6pm occupancy file. Results of the simulations are used to improve the design. This process is repeated until a satisfactory outcome is achieved.

The metric used for daylight analysis included dynamic calculations included Useful daylight illuminance (100-2000lux), and Daylight Availability (DAv) with a target illuminance of 200lux. Finally, illuminances over 2000lux were considered as glare potential.

This research examined effect of two daylight systems in different climates such as subtropical and cold climate. This is due to the range of solar angles in the locations and their compatibility with the protection offered by the shading system. In first case study from the simulations run across all variations of orientation and shading projection tested, two scenarios emerged as preferred based on the metrics used. The first is 2.00 m projection gives the greatest from sun and potential glare (GP less than 0.2 %). It is within UDI range 90% of the time; however, time outside of this range is generally below the 100 lux level. This is consistent with the shading extent, and can be considered the conservative shading option. Due to the extent of this shading option, the performance of this design is not significantly altered by changing building orientation (i.e. it rejects sun regardless of orientation).

The second scenario worth examining is the 1.75 m projection. This design gives more daylight, has a comparable UDI value (88-90%). Due to increased solar access, it has a larger GP (19% at an orientation at 90°). However rotation of the building did not seem to have a great effect on the results due to the extent of these devices. The reason is that CBDM gives an annual average performance of the device, but makes no difference throughout the day or the seasons in subtropical climate. Also due to the increased amount of sunlight, it is demonstrated that the preferred orientation is 90^0. This is where glare probability is minimal, and DA_V is maximal.

The second case study shows that the best results achieved for DA_V and UDI are for the cases with nozzle projections of 0.75 m. $DA_{V200lux}$ for this nozzle projection achieved more than 97% for most nozzle rotations and highlighting that the projection 0.75 m has no problems with over light and glare. Despite this finding, the aperture 0.75 m among the nozzles projection and the north and west rotation can provide daylight comfort levels in the Kunsthaus Graze. This projection achieved UDI on average 55% of the time without issues of glare. However rotations of the nozzle from the north have a great effect on the results due to the extent of these nozzles. The reason is that CBDM gives an annual average performance of the nozzle, but makes difference throughout the day or the seasons based on the cold climate. The sun's path also gradually changes throughout the year and so shadows vary according to the season. During the winter months the sun rises to the north of east and sets to the north of west and stays relatively low in the sky. During the summer months the sun rises to the south of east and sets to the south of west and is higher in the sky. The degree of these changes depends on the latitude. For example four particular days of the year are important for understanding the sun's annual path.

- 21 March and 23 September when day and night are of equal length (the equinoxes)
- 21 June the shortest day of the year (the winter solstice)
- 22 December the longest day of the year (the summer solstice)

For instance, the lowest GP was found at the nozzle orientation from the north and west. The high level of protection offered may be associated with insufficient daylight generally, so it is observed that the less restrictive examples where at 0.50 and 0.75 m are also to be considered as performing acceptably according to the target set for GP in this study.

In final consideration from the results section in this thesis revealed several aspects that should be remembered when choosing a method to simulate the annual availability of daylight in a building:

- Longer simulation times are not necessarily coupled with a higher accuracy of the simulation results.
- The annual simulation method should consider direct and diffuse illuminance values for each time individually.

Overall, the parametric process serves to integrate daylight device configurations with façade systems to develop a responsive system to control daylight performance. The idea is to enable customization and control of daylight comfort in interior spaces. This research is based on the two case studies of the parametric model was used for parameters of daylight device that change such as opening, height and rotation to integrate envelop façade systems. In this regard, the aim of future work will be two fold. First, to implement the control daylight device configuration and to refine and augment the facade system regarding complex designs. This will enable a broader range of solutions from the comfort daylight viewpoint. The Second future research will be on combine daylight and thermal comfort, with the expectation that this information may inform the choice of material and allow for more inclusive multi-criteria solutions such as reducing CO_2 in the building.

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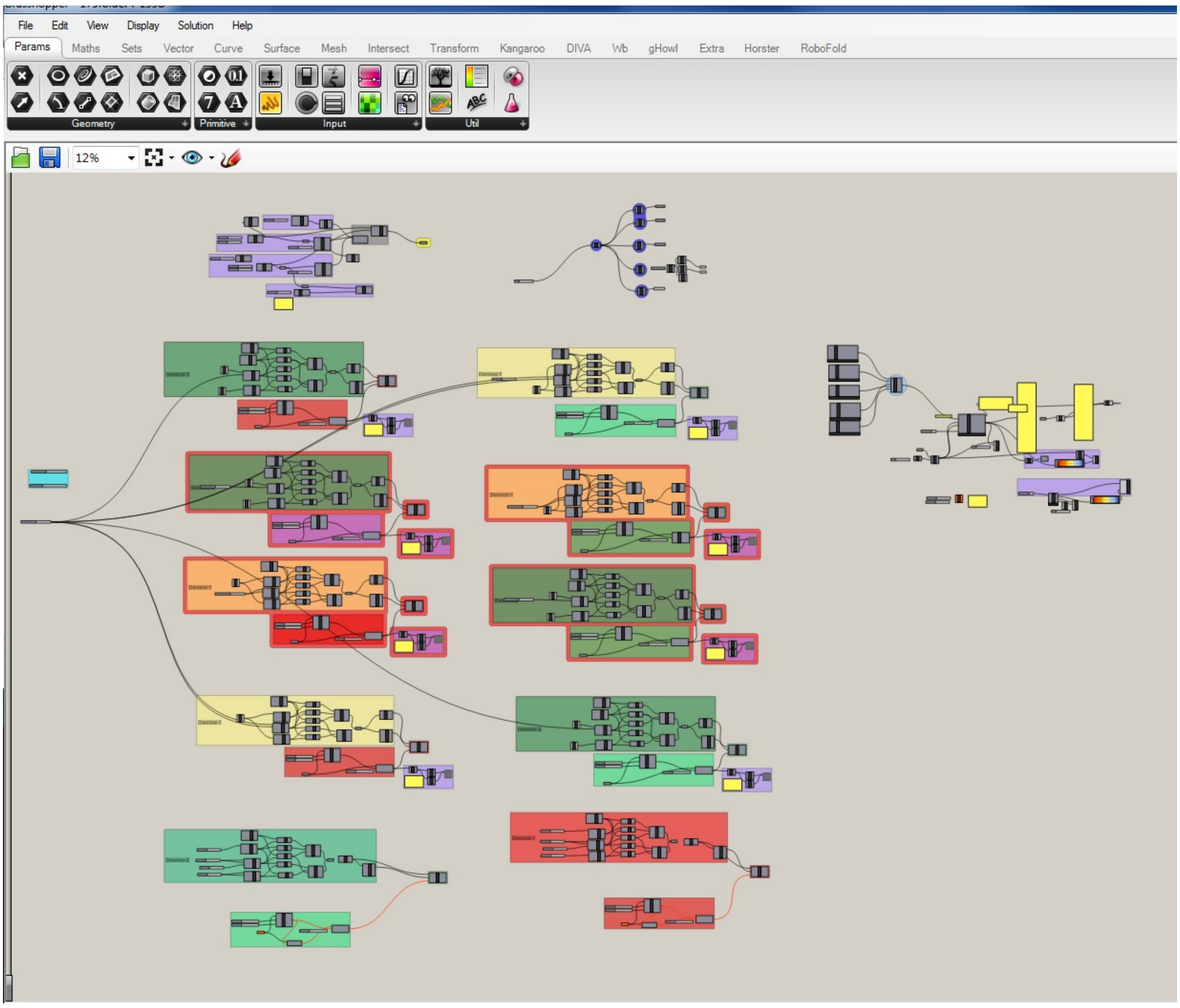
Appendices

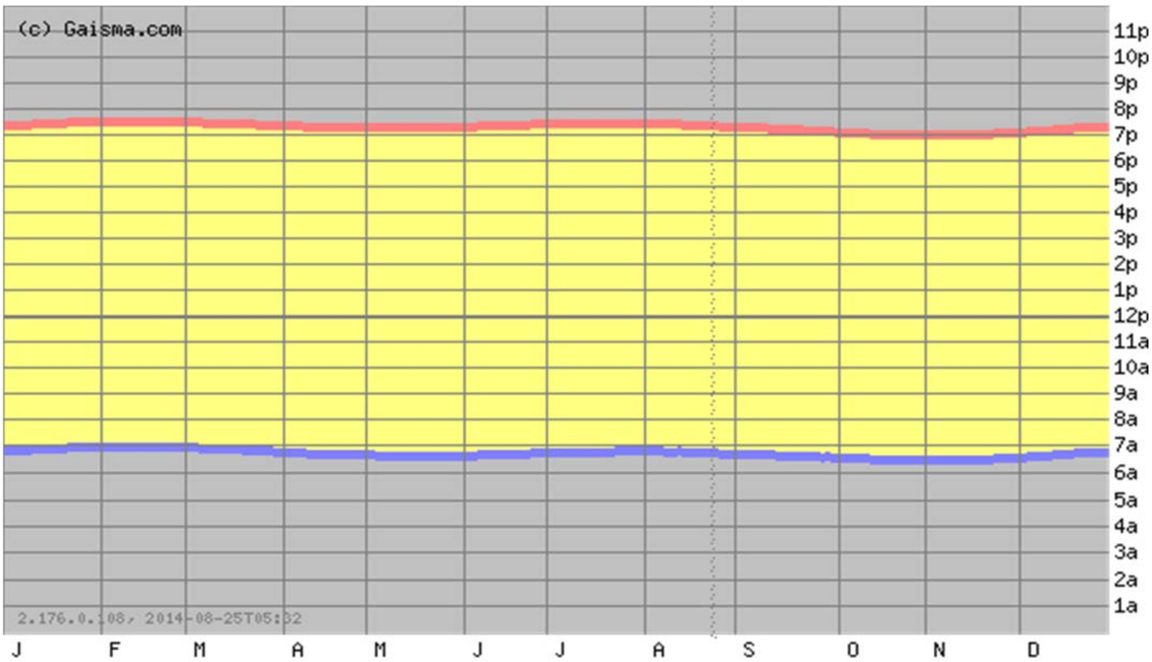
Appendix A: Esplanade building parametric process in GH plug-in.



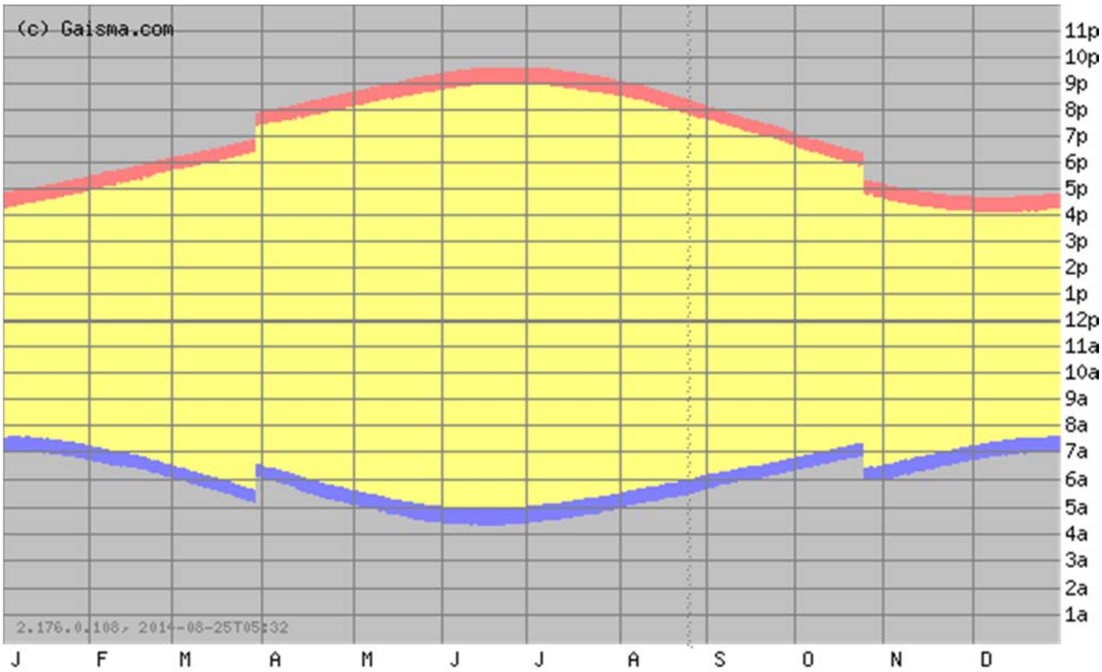
Appendix B: Useful Daylight Illuminance 100-2000 lux percentage regarding variation of daylight device projection and Esplanade building orientation from the north.

Shading device projection (m)	Building orientation (degree) 0^0	45^0	90^0	135^0
0	40	38	38	39
0.25	41	40	40	41
0.50	44	42	42	43
0.75	47	45	45	46
1.00	51	50	50	50
1.25	57	57	57	57
1.50	**70**	**70**	**70**	**70**
1.75	**88**	**89**	**90**	**88**
2.00	**89**	**90**	**90**	**90**

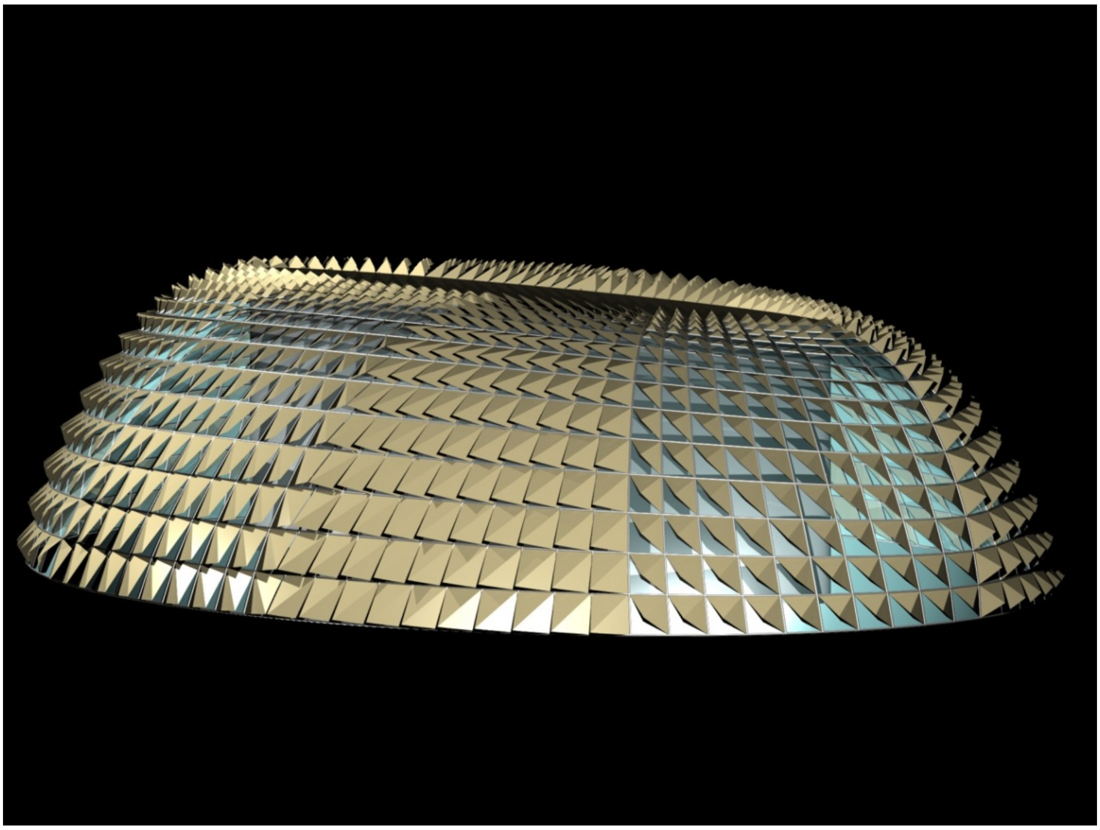
Appendix C: Singapore sunrise and sunset times graph



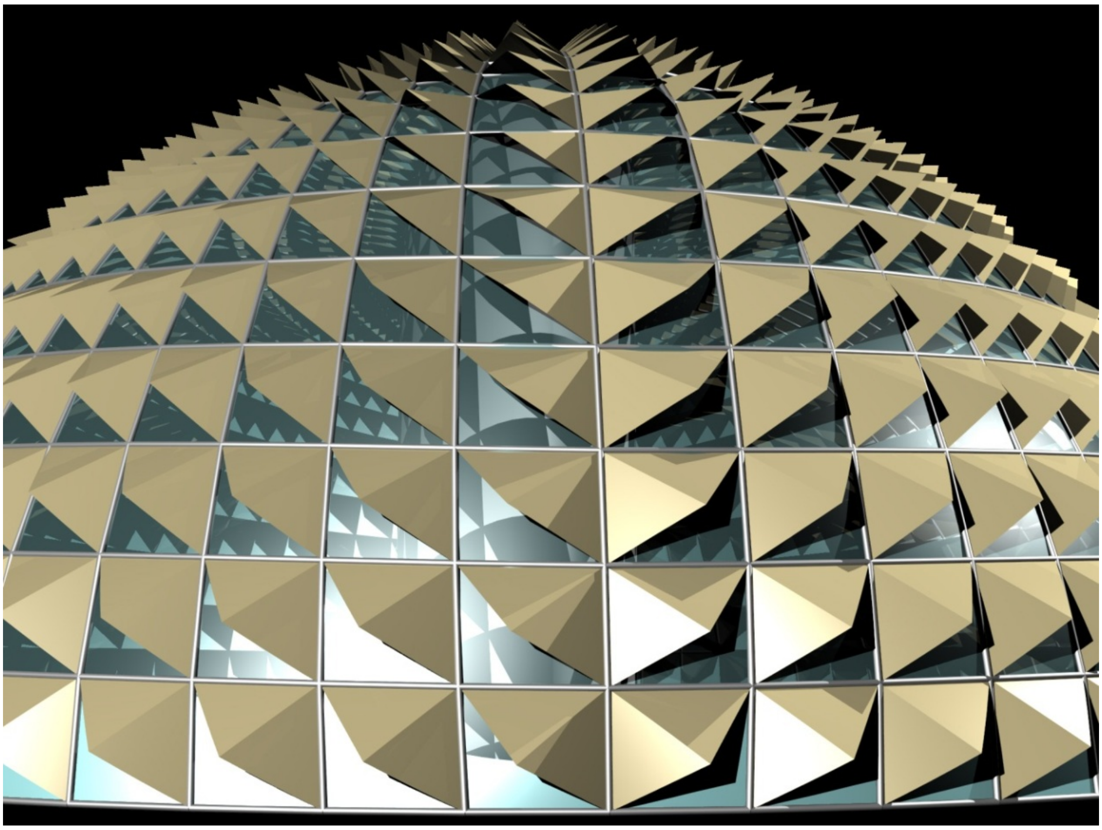
Appendix D: Graz, Austria sunrise and sunset times graph



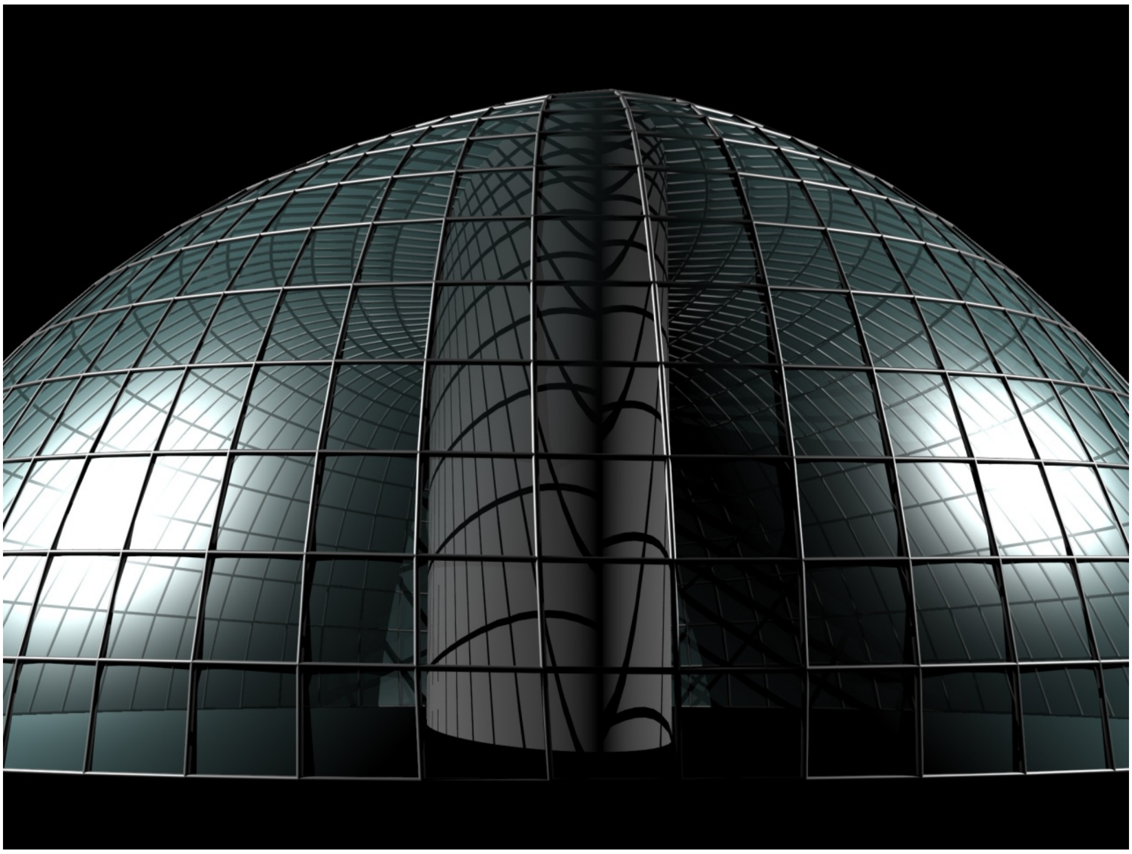
Appendix E: Esplanade cladding system, rendering by Rhinoceros.



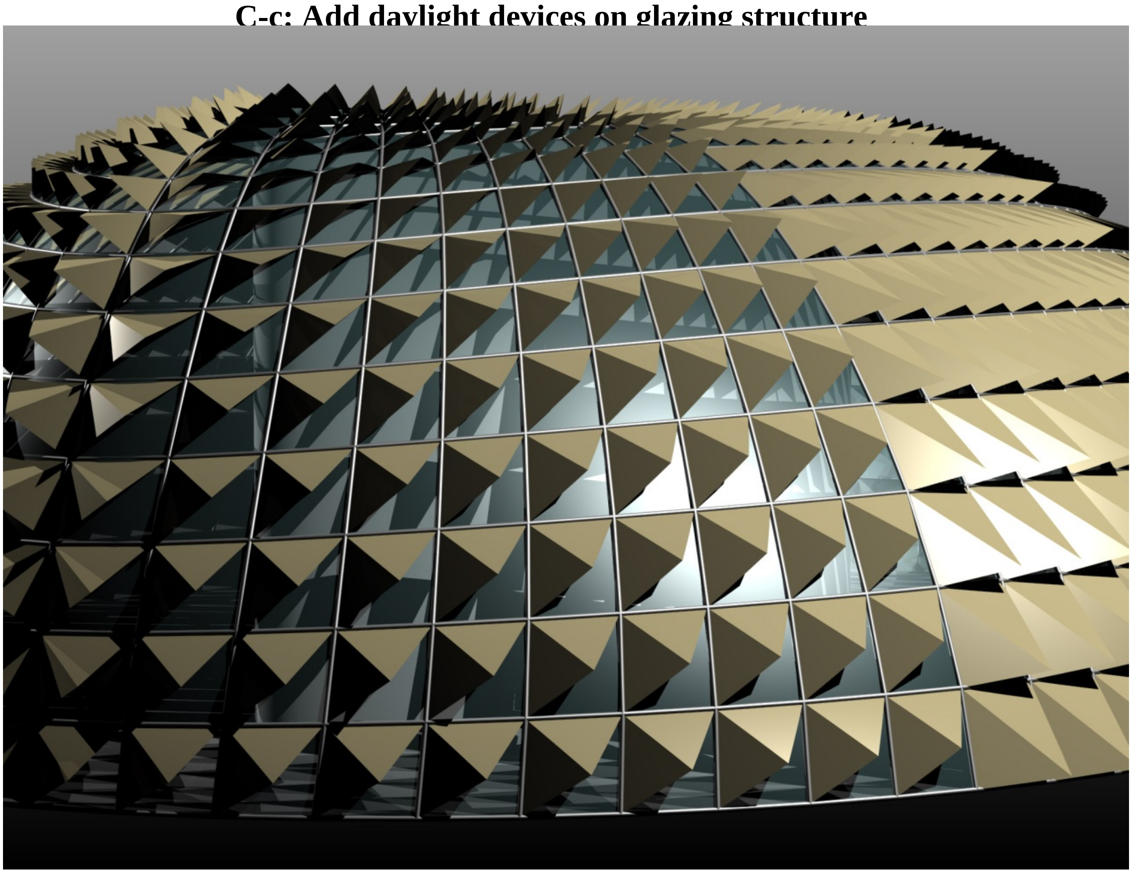
E-a: Cladding system-North Elevation



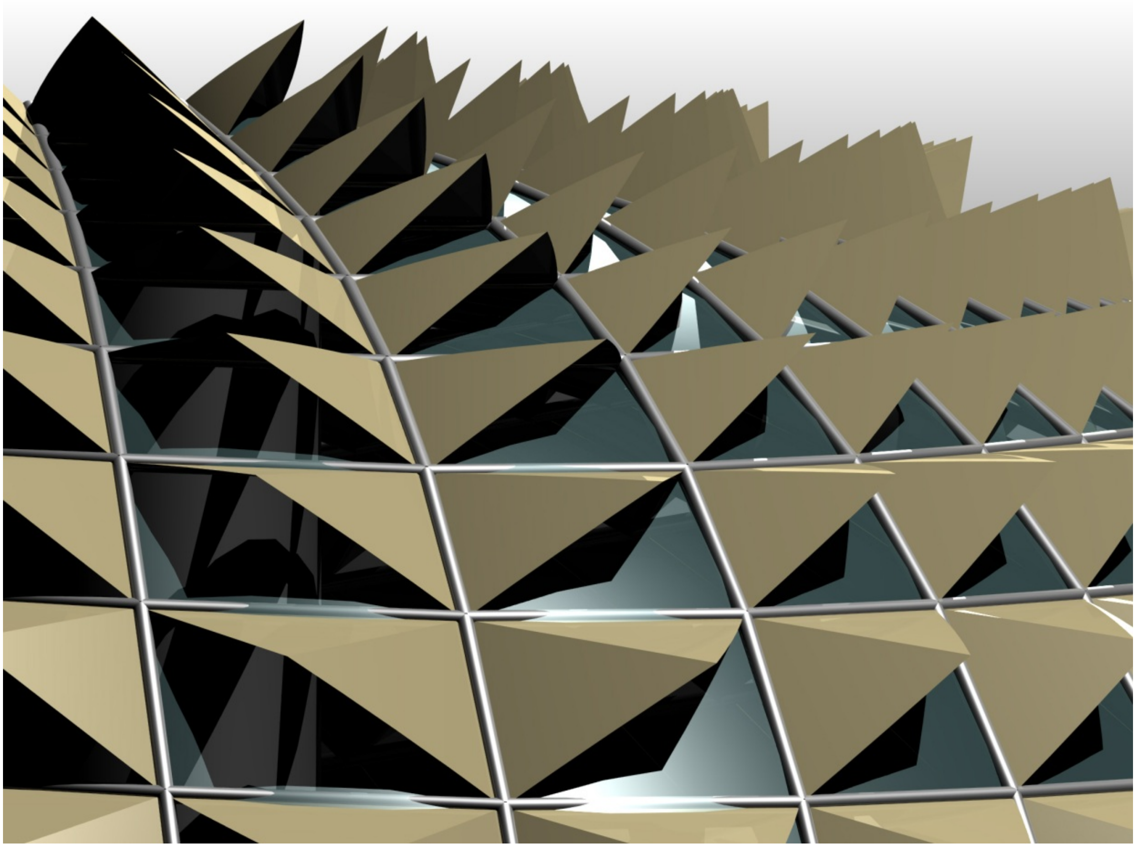
E-b: Glazing structure

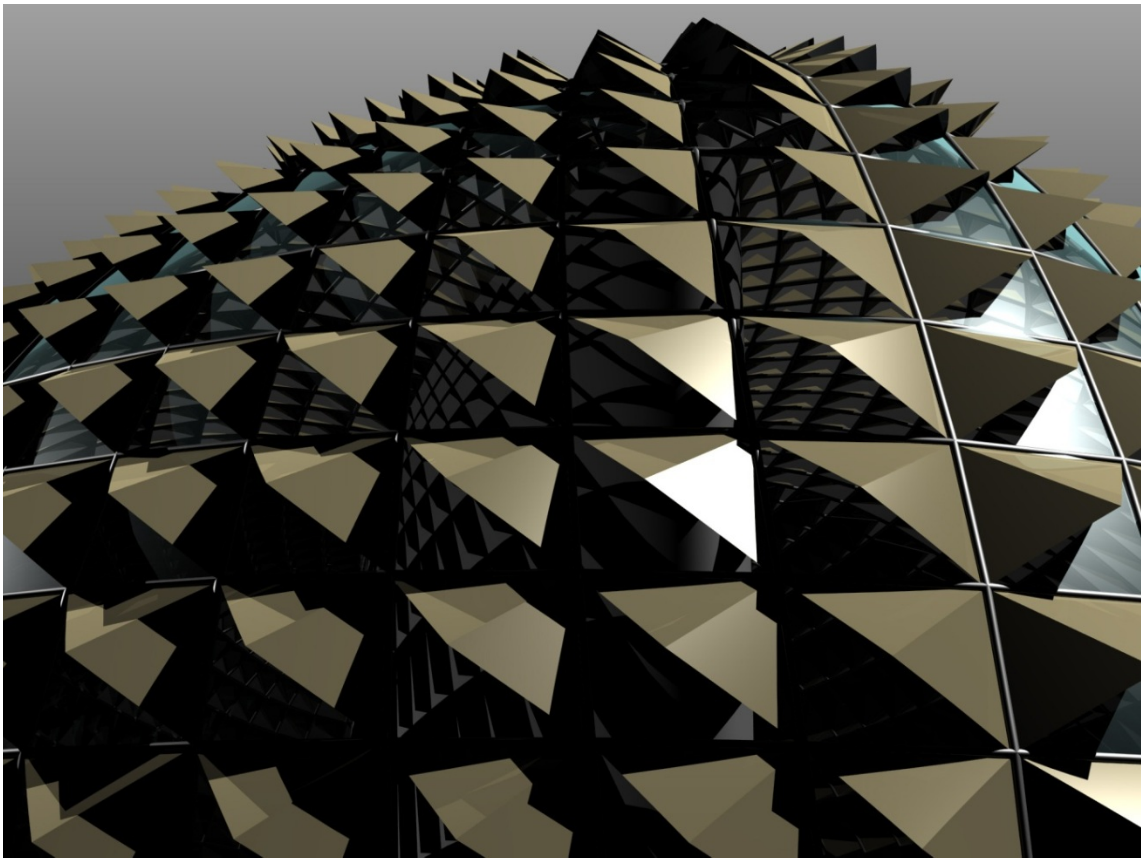


C-c: Add daylight devices on glazing structure

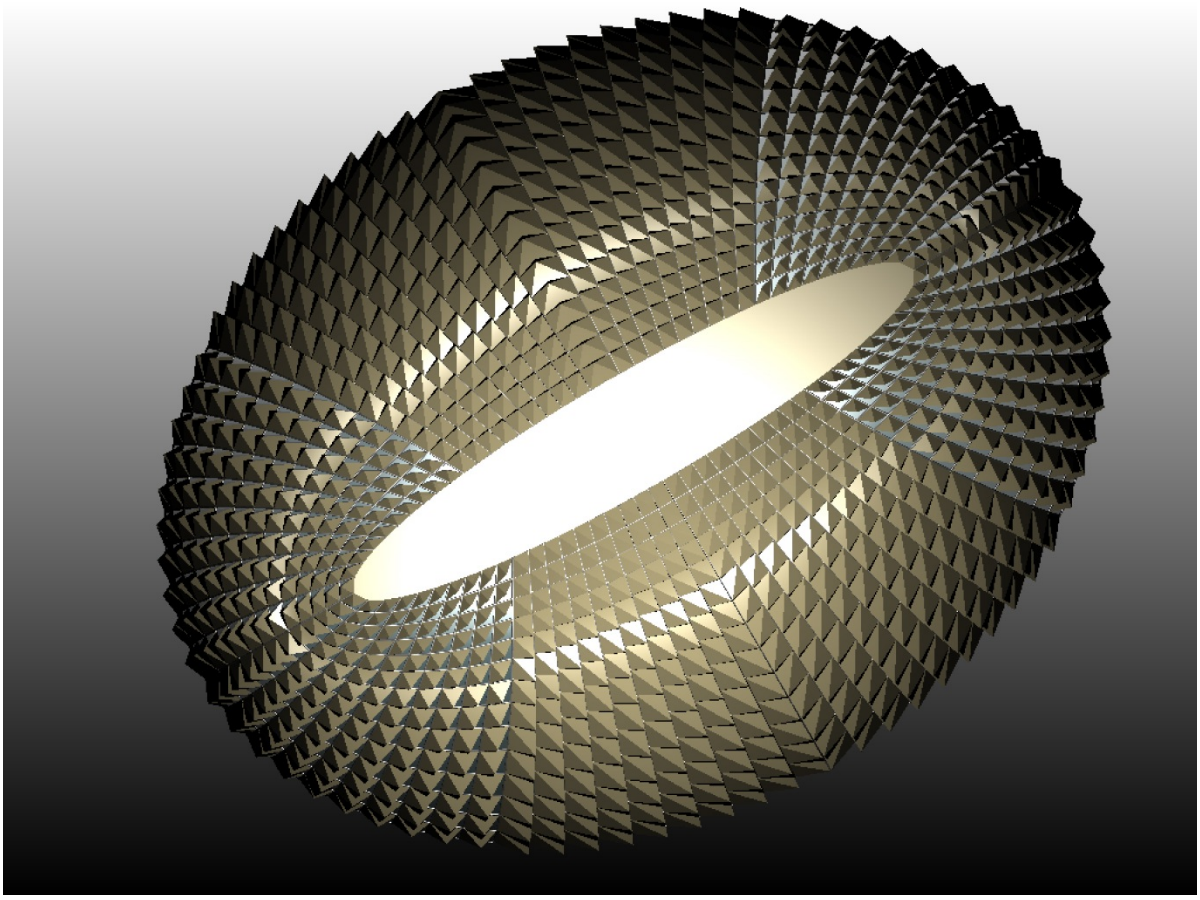


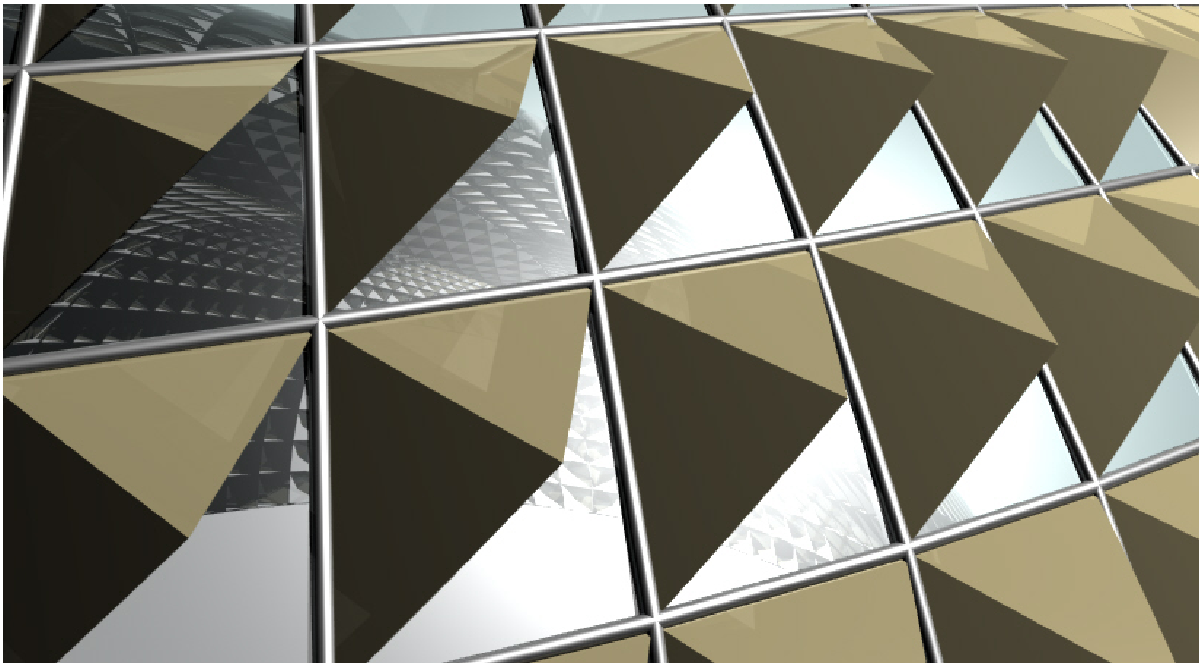
E-d: Daylight device projection



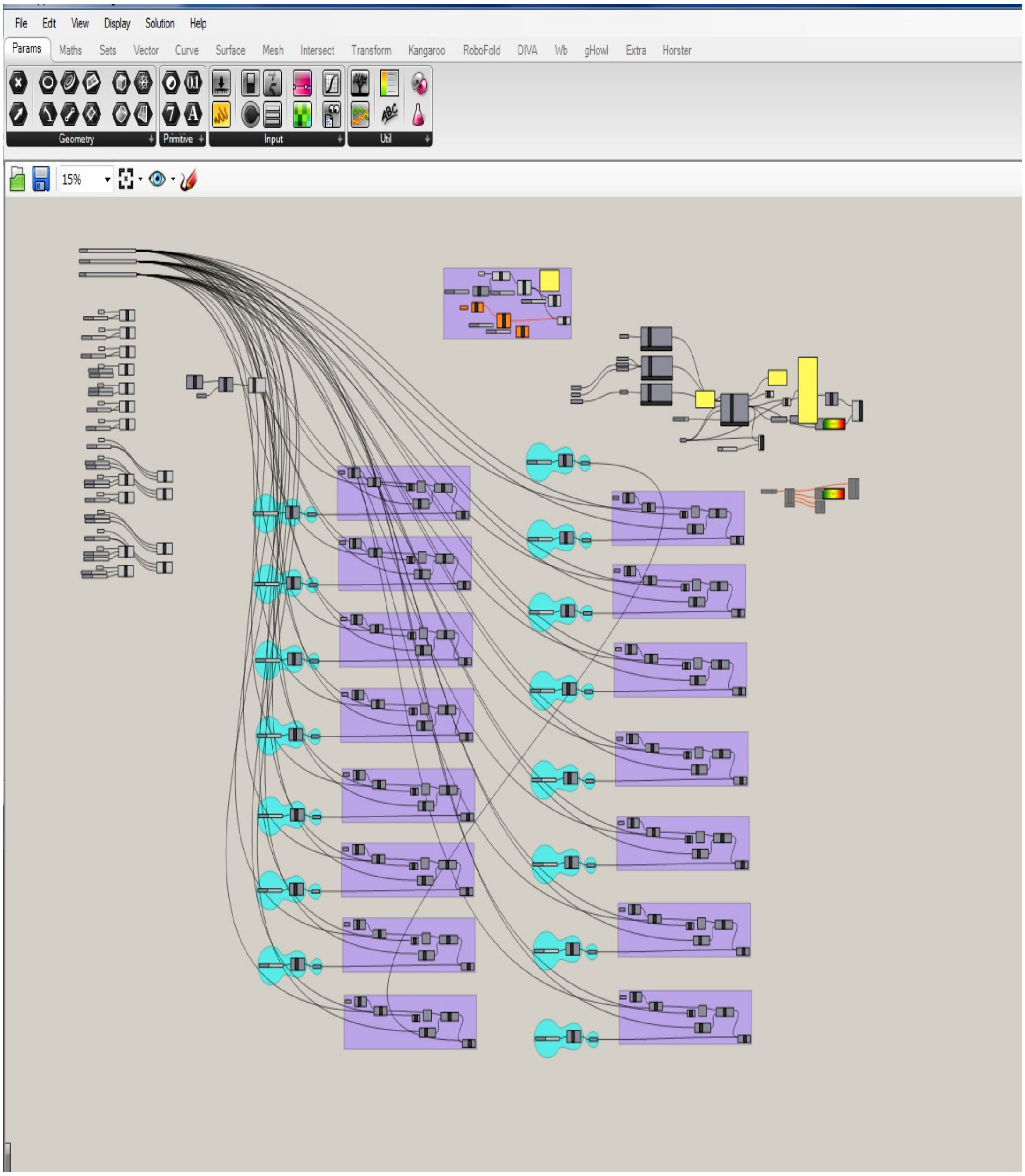


E-e: Esplanade building top view

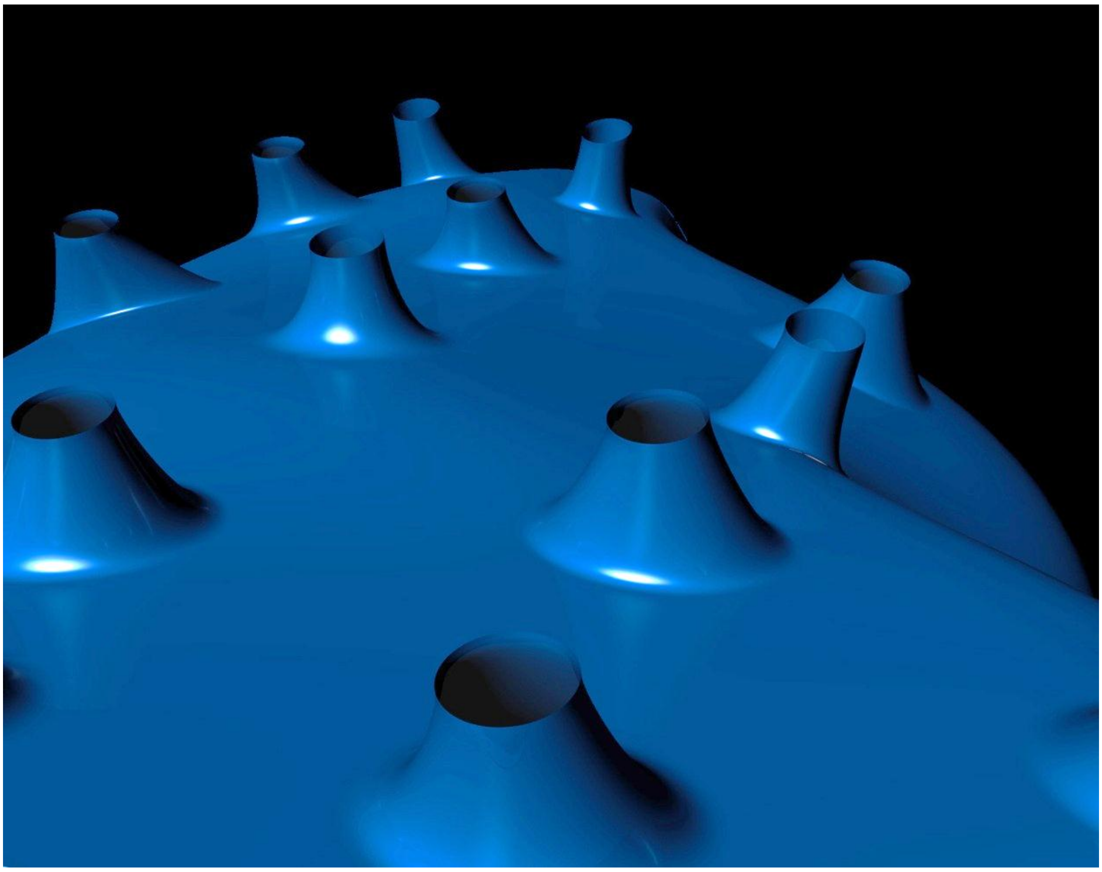




Appendix F: Kunsthaus Graze parametric process in GH plug-in.



Appendix G: Kunsthaus Graze cladding system, rendering by Rhinoceros.



G-a: Nozzle rotations top view